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Sixth NSF Grantees' Conference on Production Research and Technology, Held at West Lafayette, IN on September 27-29, 1978

Purdue Univ, Lafayette, IN

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SIXTH

NSF GRANTEES' CONFERENCE ON PRODUCTION RESEARCH AND TECHNOLOGY

September 27-29, 1978

West Lafayette, Indiana

'RA-780392

ASRA INFORMATION RESOURCES
NATIONAL SCIENCE FOUNDATION

PURPOSE

The National Science Foundation's (NSF) Grantees' Conferences on Production Research and Technology are forums for presenting and discussing work done in a particular group of National Science Foundation sponsored projects, and closely related industrial projects. The Conferences' focus is advanced research and development in automation and production technologies, with special reference to the discrete goods industries. It brings together grantees of NSF to present recent research results in manufacturing technology research, as well as a select group of managers, scientists and engineers most responsible for applying research results to the increase of productivity of American industry.

Attendance (typically 200-300) is by invitation and includes a large number of industrial representatives as well as Foundation personnel, grantee personnel, and various labor, government, and educational representatives.

Present plans call for conferences at yearly intervals, with sponsorship rotating among the various NSF grantees. The first Conference was held at Stanford Research Institute on March 27-28, 1974. The second Conference was held at the University of Rochester on January 7-9, 1975. The third Conference was held at Case-Western Reserve University on October 28-29, 1975. The fourth Conference was held at the Illinois Institute of Technology Research Institute on November 30, December 1-2, 1976. The fifth Conference was hosted by The Charles Stark Draper Laboratory and the Massachusetts Institute of Technology on September 26-29, 1977. The sixth Conference hosted by Purdue University was held at West Lafayette, Indiana, September 27-29, 1978.

Copies of the second, third, fourth and fifth Grantees' Conferences may be obtained from the National Technical Information Service. Copies of the sixth Grantees' Conference may also be obtained from the National Technical Information Service or, while copies are available, by writing to:

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16. Abstract (Limit: 200 words)

This collection of papers on manufacturing technology research was presented at the Sixth Annual NSF Grantees' Conference. The first paper discusses the goals, history, scope, and activities of the Production Research and Technology Program. Several research presentations concern geometric modeling, a computer-aided injection molding system, a design for economic manufacture, optional planning of computerized manufacturing systems, and the design and analysis of such systems for small parts with emphasis on non-palletized parts of rotation. Subsequent papers include progress in flexible automation and materials handling research, modeling and analysis of materials handling systems, a generalized manufacturing simulator, in-process optical gauging for numercial machine tool control and automated processes, holographic laser material processing, industrial robot control systems, and computer integrated assembly systems. A list of attendees comprises the appendix.

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SIXTH

NSF GRANTEES' CONFERENCE
ON
PRODUCTION RESEARCH
AND
TECHNOLOGY

September 27-29, 1978

West Lafayette, Indiana

Hosted by

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Any opinions, findings, conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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PRODUCTION RESEARCH AND TECHNOLOGY

Dr. Bernard Chern
National Science Foundation, Washington, D. C. 20550

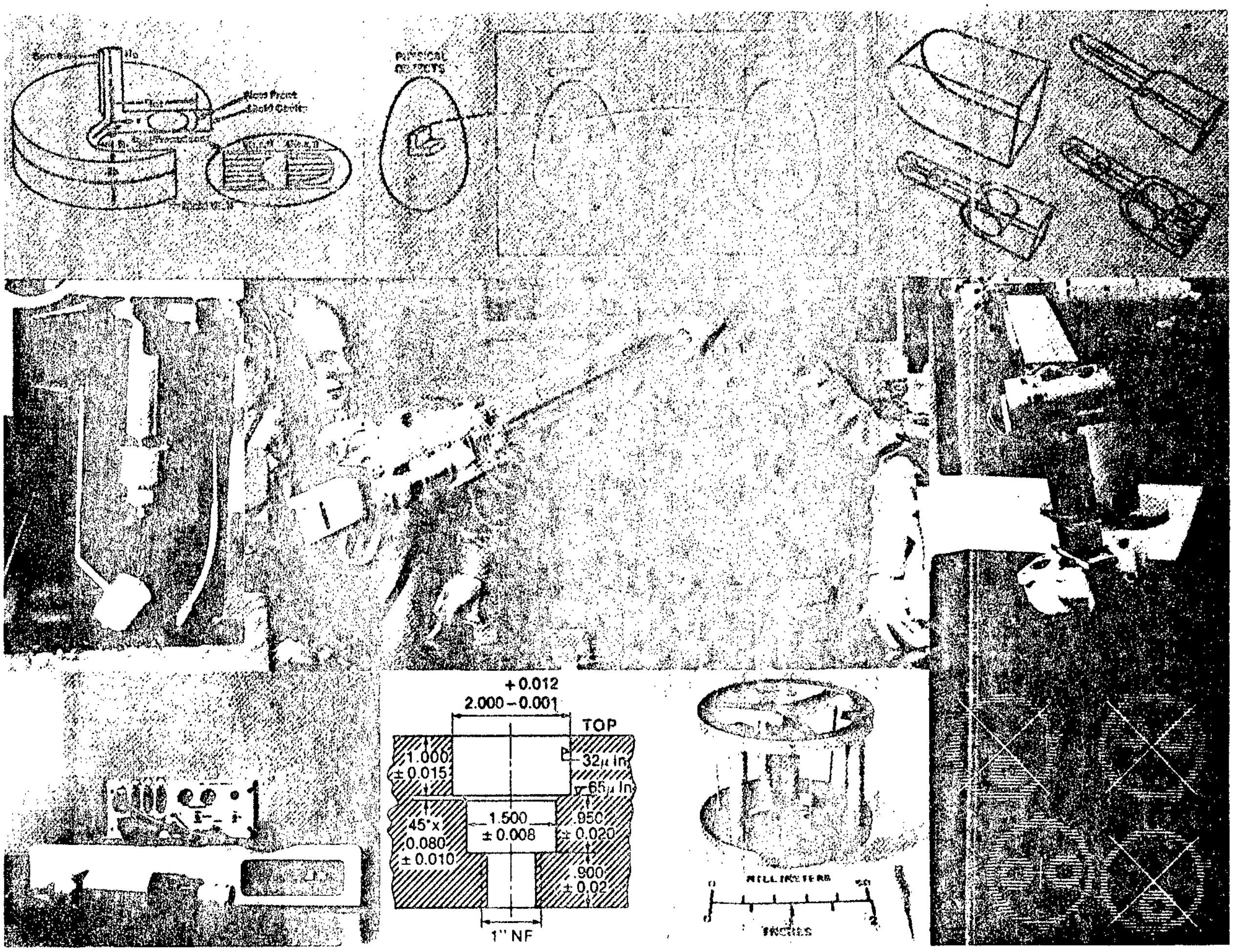

Fig. 13

The Production Research and Technology program began in 1971 and encourages research on automation and new-process technology. It is concerned with the technical problems which underly both the physical transformations of objects and the informational transformation necessary to understand, model, control, and carry out manufacturing operations.

As an applied science program, it has both utilitarian and intellectual goals (Figure 14). There are two intellectual goals. The first is to establish a science base for manufacturing. Today, large parts of manufacturing are still experience-based. They do not rest on a coherent body of analytically derived knowledge having wide applicability. This program seeks to provide such an underlying knowledge base. The second goal is to transfer intelligence from man to machine. The first industrial revolution involved the transfer of skills from man to machine, and much has been accomplished in this area. The second industrial revolution, which is in its infancy, involves the transfer of intelligence from man to machine.

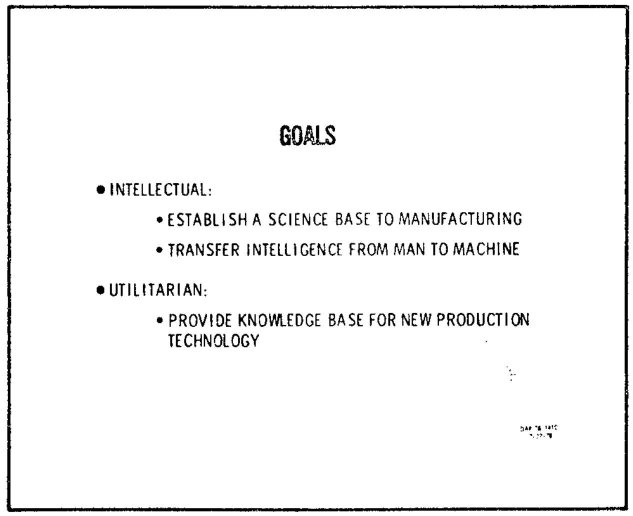

Fig. 14

The utilitarian goal is to provide the knowledge needed to generate new production technologies which may yield major increases in industrial productivity. Of particular interest is the class of versatile, programmable, computer-based production technologies which will be required in the future for automating the manufacturing of products made in small batches. As much as 75% of discrete products today are manufactured in small batches. Thus, significant improvements in automation could lead to major productivity increases.

The program has always relied on unsolicited proposals. Universities form its core, and industrial collaboration is encouraged. Strong linkages exist to other Foundation programs. The program structure reflects the functional components of the manufacturing process. (Figure 15). Manufacturing consists of designing the product and its constituent parts, specifying their characteristics and details, planning the specific processes by which they would be manufactured, manufacturing of parts, the flow of these parts through factory, and finally, their inspection and final assembly into a product. This process constitutes the informational and physical transformations needed to convert stock into end products.

In this program review only those research issues involved with generating a knowledge base for automation are discussed. In order to provide the knowledge base for

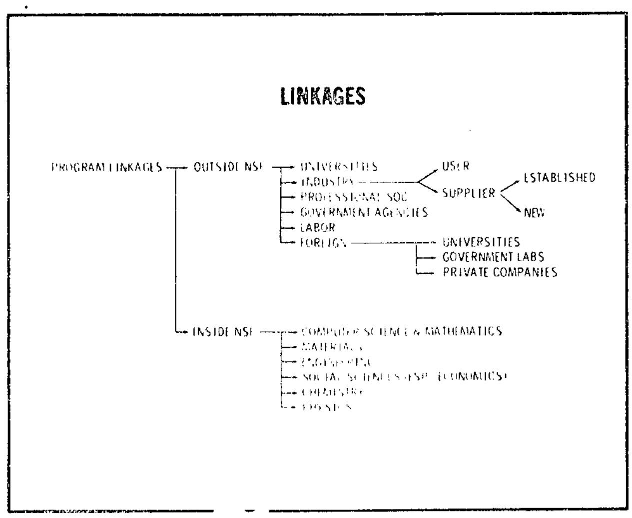

Fig. 15

future automation of manufacturing, one must address two broad research issues: representation, including description and modeling, and planning (Figure 16).

RESEARCH ISSUES FOR AUTOMATION

- REPRESENTATION
  - ABSTRACT CHARACTERIZATION OF:
    - MECHANICAL PARTS, MACHINE TOOLS, FIXTURES, ETC.
    - PHYSICAL TRANSFORMATION PROCESSES, E.G., MACHINING OR FORGING
- PLANNING
  - DEVELOP ALGORITHMS WHICH:
    - COMPOSE SEQUENCES OF TRANSFORMATIONS WHICH TAKE INITIAL OBJECT INTO FINISHED PART

Fig. 16

For representation, mathematical frameworks are required to characterize in an abstract manner: machine tools, mechanical parts, stock, fixtures, partially finished work pieces, etc. The same or related mathematical frameworks are needed to characterize the physical transformation processes involved in manufacturing; for example, machining, forging, and casting. Having accomplished these abstract characterizations, planning then consists of composing sequences of mathematical transformations which cause the initial representation of the stock or partially finished part to be carried into the representation of the finished part. The next step in automating the manufacturing process is to implement these mathematical representations into computer programs. These programs, when interfaced to machine tool sensors and other parts of the manufacturing system, complete the automation process. The production research and technology program to date has supported work in all of these facets of automated manufacturing. Illustrative of this work are two projects underway at Purdue University and the University of Rochester.

At Purdue, a university/industry research group has developed a method of providing a computer-readable characterization of machine surfaces, such as holes and bounded plane surfaces, such as keyways, slots, steps, and grooves (Figure 17). In addition, they are developing computer programs which automatically select the

MOSHE BARASH, PURDUE UNIVERSITY

"THE OPTIMAL PLANNING OF COMPUTERIZED MANUFACTURING SYSTEMS"

UNIVERSITY/INDUSTRY TEAM

- CATERPILLAR
- PURDUE UNIVERSITY
- INGERSOLL-RAND
- SUNDSTRAND MACHINE TOOL

RESULTS:

- COMPUTERIZED CHARACTERIZATION OF MACHINED SURFACES
- COMPUTER PROGRAMS FOR SELECTING TOOLS AND MACHINES FOR PRODUCING THESE SURFACES

Fig. 17

proper tools, machines, and sequences of machining operations to produce these surfaces.

At Rochester, another university research group collaborating with industry has been working on the representation problem in automation and has succeeded in abstractly characterizing discrete parts (Figure 18).

HERBERT VOELCKER, UNIVERSITY OF ROCHESTER
"MANUFACTURING MODELING AND PLANNING"

UNIVERSITY INDUSTRY TEAM

- BOEING AIRCRAFT
- EASTMAN KODAK
- GENERAL MOTORS
- GLEASON WORKS
- ROCHESTER UNIVERSITY
- XEROX CORPORATION

RESULTS:

- MATHEMATICAL MODELS FOR DISCRETE PARTS
- COMPUTER LANGUAGE TO SPECIFY PARTS (PADL)
- COMPUTER SYSTEM IMPLEMENTATION OF MATHEMATICAL MODELS
- AUTOMATIC GENERATION OF MECHANICAL DRAWINGS

Fig. 18

Primitive solids are represented by mathematical point sets. Shape-specification of parts is accomplished through their definition as compositions of primitive solids by use of the regularized set operators; difference, union, and intersection. These operators can be applied to arbitrarily complex objects; thus, material removal and addition processes can also be characterized by this mathematical framework. This has provided the base for a computer language called the "Part and Assembly Description Language (PADL)," used to specify the geometry of the part. The mathematical model of the part embedded in the computer can then be used to calculate any geometrical property of the part. Additionally, the model can be turned, sectioned, scaled, and displayed in various ways. Since the part now exists in the "mind" of the computer, its dimensions and tolerances can be produced automatically. The first applications to date have been to automatically generate mechanical drawings of parts. Rochester is now turning its attention to the abstract representation of machining processes and planning. Thus, the research at Purdue will link Rochester's abstract work to actual machining operations.

Manufacturing is not a scientific discipline. Since the program encompasses research at different levels, namely, the tool, machine, ensembles of machines, and manufacturing as a system, it draws upon researchers from mathematics, physics, artificial intelligence, computer science, economics, engineering, and so on (Figure 19). Typical investigators are located in a variety of institutions, ranging from the major research universities to the not-for-profits, to small businesses (Figure 20). Users represent all of manufacturing: batch, mass production, and continuous process. Their relationship to the research

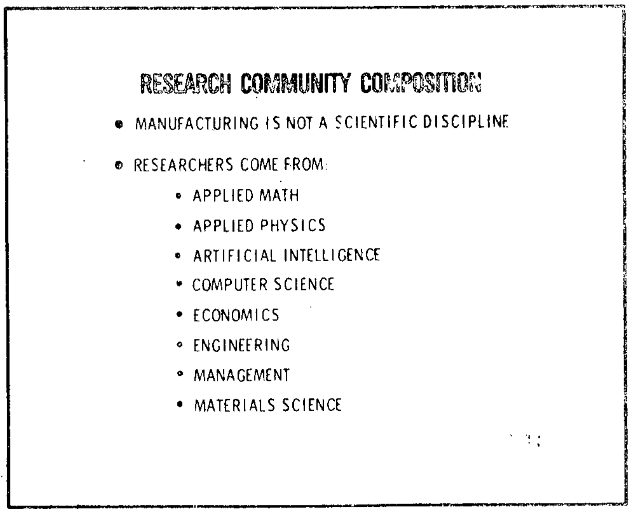

Fig. 19

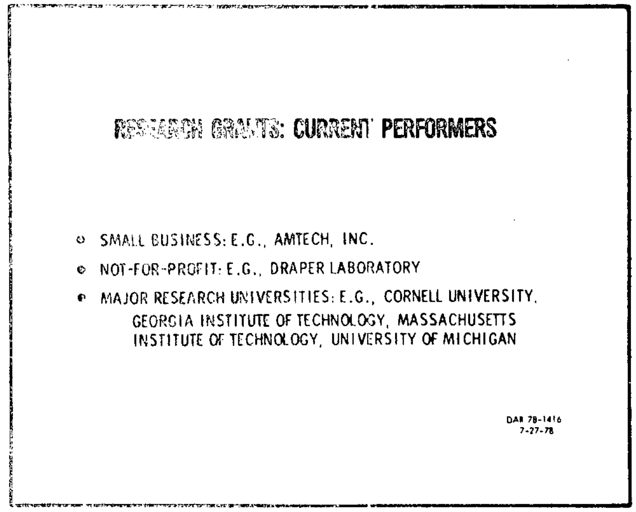

Fig. 20

supported by the program varies. Some users, as represented for example in the top group in Figure 21, possess a corporate research capability which enables them to actively follow and actually participate in the research. A second group consists of the supplier industries. Some suppliers of machine tools are listed. They perform some exploratory research and possess strong development capabilities, which enables them to follow and to adopt research results. The final group of firms have little, if any, R&D capability and rely almost exclusively on suppliers to produce new technologies. The segments of the user community which do research focus primarily on product development. Process research is mostly incremental, and it is subjected to return-on-investment calculations with short payback periods, usually of less than three years.

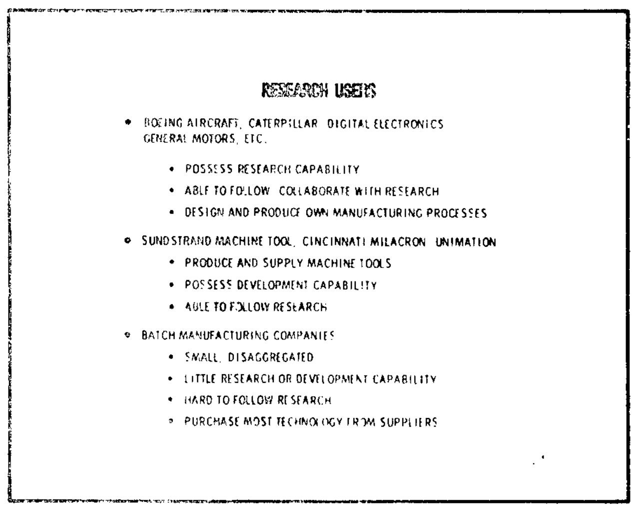

Fig. 21

The production research and technology program appears to be the only Federal program concerned with and supporting generalized manufacturing research--that is, the creation of new knowledge about the manufacturing process and possible new technologies which may significantly affect manufacturing as currently performed. Programs funded by the mission agenices are concerned with the state of the art in manufacturing as it applies to their perceived needs. The manufacturing technology programs in the Department of Defense

require demonstrations of technical feasibility of manufacturing method before they will invest procurement dollars for full-scale development.

In general, research in the private sector's manufacturing industries is product-oriented. To the extent that research is done, it is usually proprietary, specific to a product, defensive, and these days, typically short-range (Figures 22).

OTHER SUPPORTERS OF MANUFACTURING RESEARCH

FEDERAL AGENCIES:

- DOD: AIR FORCE, NAVY, ARMY
  - MISSION ORIENTED
  - MUST DEMONSTRATE DIRECT COST-SAVINGS
- NASA
  - MISSION ORIENTED
  - TECHNOLOGY UTILIZATION
- DOC
  - FOCUSED ON ECONOMICALLY THREATENED INDUSTRIES

- PRIVATE SECTOR
  - PROPRIETARY
  - PRODUCT SPECIFIC
  - DEFENSIVE
  - SHORT RANGE

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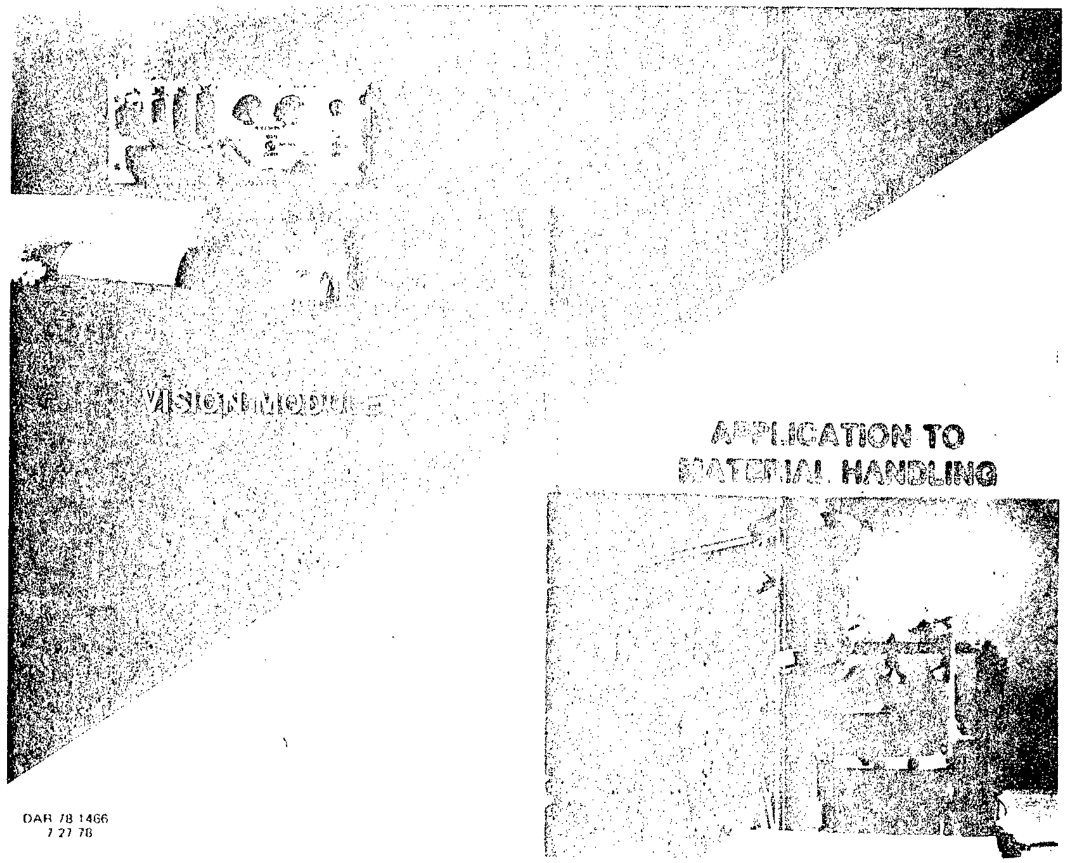
Fig. 22

It is significant that the Production Research and Technology program's support of research has stimulated interest in user and supplier companies in pursuing promising avenues of manufacturing research. For example, the General Motors research lab has instituted programs on computer vision and robotics which have drawn directly on NSF-supported work at Stanford Research Institute International and Stanford University. Figure 23 is a picture of a "trainable" materials-handling system using vision. Illustrated are metal castings which have a distinctive two-dimensional computer image on a contrasting background. The system will recognize individual parts, determine their position and orientation, feed the information into a unimate robot which will track, pick up, and transport the parts to some desired location. Figure 24 shows the robot vision system and the picture of the 2 dimensional image which the computer "sees." GM and other manufacturing groups have also benefited from some of the path control work that was done at Stanford and SRI.


VISION MODULE
APPLICATION TO MATERIAL HANDLING
DAR 78 1466
7 27 78


DAR 78-1
7-27-7

Similarly, the General Electric Corporate R&D Center at Schenectady, New York has initiated an assembly research group, drawing on other NSF-supported work at University of Massachusetts, C.S. Draper Lab, SRI International, University of Rhode Island, and Purdue University.

Figure 25 shows a system which makes use of a clever device called a "smart wrist," resulting from work supported at Draper Lab. In effect, it mechanically separates displacements and rotations so that very close-fitting insertations can be made. Figure 25a shows a ball bearing being inserted into the end of a Ford Motor Company alternator. The alternator's casing and bearing are shown in Figure 25b.

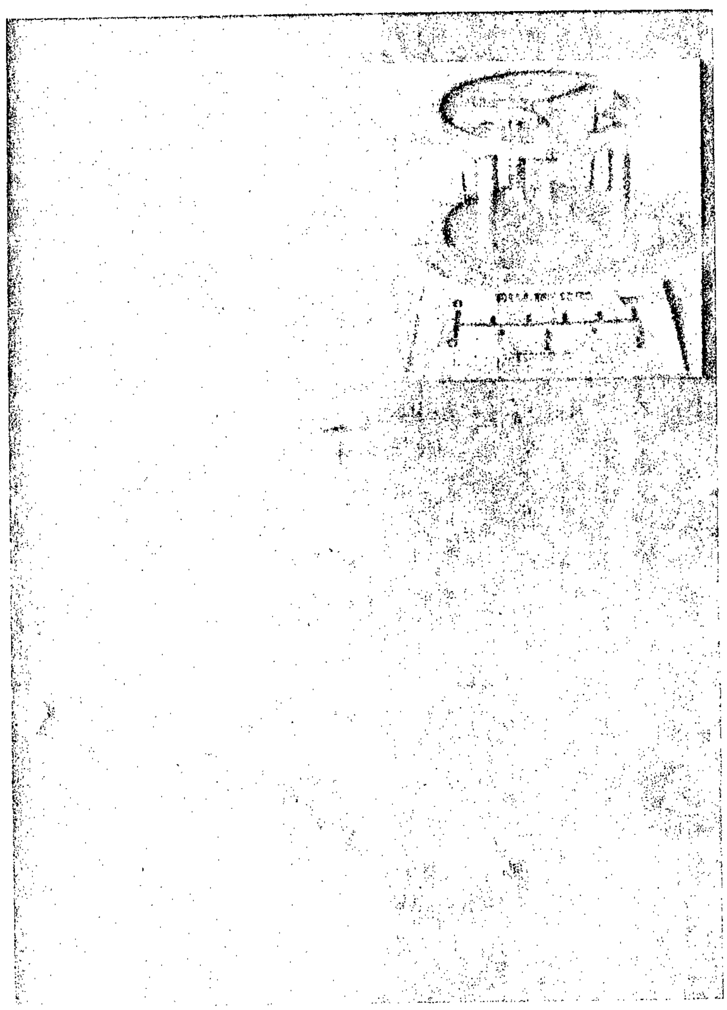


Fig. 25

Finally, a robotics manufacturer, Unimation, Inc., in Connecticut has formed a west coast research group, composed of several former graduate students of the artificial intelligence lab at Stanford. This new Group is developing an assembly robot and a computer language for Unimation which also draws directly on NSF-supported work.

It must be emphasized that some of the largest, most systematic and innovative research programs in manufacturing are not to be found in the United States, but abroad. The importance of manufacturing research is clearly recognized by some of our major industrial competitors. Coordination between the Production Research and Technology program and manufacturing R&D performed in the United States and abroad is achieved through a number of mechanisms (Figure 26). For example:

- An industrial affiliates group, consisting of Black and Decker, Xerox, Ford Motor Company, and three or four other companies, meets quarterly with a research team at Cornell, which is investigating basic problems in polymer injection molding;

- An annual grantee conference brings together university, industrial researchers, and mission agencies to discuss research in manufacturing, in particular those projects supported by NSF. (The mix of institutions attending these conferences is illustrated in Figure 27.) In 1977, 20 universities and 54 companies sent over 200 people including 104 industrial attendees, several from foreign universities and companies. At these conferences industrial researchers usually give talks on the status of their work.

COORDINATION MECHANISMS

- INDUSTRIAL AFFILIATE GROUPS
- GRANTEE CONFERENCES
- PEER REVIEWS
- PROJECT ADVISORY COMMITTEES

Fig. 26

FIFTH NSF GRANTEES' CONFERENCE ON PRODUCTION RESEARCH

- REGISTERED ATTENDANCE WAS 204 PLUS GRADUATE STUDENTS FROM THE BOSTON AREA.
- 20 UNIVERSITIES AND 3 NONPROFITS SENT 86 ATTENDEES.
- 54 DIFFERENT COMPANIES SENT 104 INDUSTRIAL ATTENDEES.
- AMONG THE 23 NONPROFITS AND UNIVERSITIES WERE:
  - CARNEGIE-MELLON UNIVERSITY
  - CASE WESTERN RESERVE UNIVERSITY
  - CORNELL UNIVERSITY
  - MASSACHUSETTS INSTITUTE OF TECHNOLOGY
  - UNIVERSITY OF MICHIGAN
  - PURDUE UNIVERSITY
  - UNIVERSITY OF ROCHESTER
  - STANFORD UNIVERSITY
  - TEXAS A&M UNIVERSITY
  - UNIVERSITY OF WISCONSIN-MADISON
  - TECHNICAL UNIVERSITY OF BERLIN, GERMANY
  - UNIVERSITY OF TOKYO, JAPAN
- AMONG THE 54 DIFFERENT COMPANIES REPRESENTED WERE:
  - ALCOA
  - AMP, INC.
  - BELL TELEPHONE LABS
  - BENDIX CO.
  - BOEING CO.
  - CATERPILLAR TRACTOR
  - CHRYSLER CORPORATION
  - CINCINNATI-MILACRON
  - COMPUTERVISION INC.
  - DIGITAL ELECTRONICS
  - FIAT, ITALY
  - FORD MOTOR COMPANY
  - GENERAL MOTORS TECHNICAL CENTER
  - HEWLETT PACKARD
  - HITACHI, JAPAN
  - HONEYWELL INC.
  - IBM
  - KODAK
  - 3 M COMPANY
  - GENERAL ELECTRIC CO.
  - OKI ELECTRIC IND. CO., JAPAN
  - OLIVETTI, ITALY
  - SIEMENS, WEST GERMANY
  - SUNDSTRAND MACHINE TOOL
  - UNIMATION INC.
  - UNITED TECHNOLOGIES
  - WARNER AND SWAZEY
  - WESTERN ELECTRIC
  - WHIRLPOOL CORPORATION
  - XEROX CO.

Fig. 27

To conclude: basic research in fields like computer sciences, artificial intelligence, mathematics, physics, and materials research and engineering, which have potential application in manufacturing, is finding a home in the Production Research and Technology program. This program also offers a meeting place for users to interact with researchers thus accelerating the application of this work to actual manufacturing.

GEOMETRIC MODELING & ITS APPLICATIONS: A PROGRESS REPORT

by

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August 1978

PROGRAM OBJECTIVES

The Production Automation Project is concerned with theories of mechanical manufacturing, design, inspection, and assembly, and with relevant technologies and systems. Since 1973 we have been pursuing the following objectives.

-- The development of schemes to model the geometry of objects (parts, assemblies, fixtures, ...), and to model also the effects of processes (e.g. machining) which modify the geometry of objects.

-- The development of algorithms to produce automatically, from models of parts, stock, and processes, manufacturing plans and command data for NC machine tools.

-- The design and implementation of software systems which embody such description and planning schemes.

Our work has been concentrated for the past several years on theories and software technologies for object modeling. We believe that the object modeling problem is now solved at the research level for a large class of industrial parts and assemblies, and we are therefore redirecting our efforts toward machining-process modeling and planning research.

* * *

PROGRAM ACHIEVEMENTS: 1972-1977

Our work began with a series of technology surveys covering Computer Graphics, Industrial Graphic Systems, Part Programming Languages and Systems, and Numerical Controller technology. Only the last is well understood in a scientific and engineering sense; the other technologies are collections of partial and largely ad-hoc "solutions" to ill-defined problems. We concluded that manufacturing as a whole lacks abstract organizing principles, i.e. theory in the classical scientific sense.

A central deficiency -- the lack of powerful mathematical and computational means for handling solid geometry -- became apparent almost immediately. Because manufacturing is strongly "geometrical" in character, we decided to seek as our first order of business a mathematical modeling domain for the geometry of solid objects and transformations thereon.

By early '74 we had settled on the basic elements of a simple, consistent theory of solid modeling. Briefly, solids may be modeled as compact, regular, semi-analytic sets of points in E3 (Euclidean 3-space), and transformations on solids may be modeled by the rigid motions (translation, rotation) and regularized versions of the conventional set operators -- intersection, union, and difference. The last two operators provide means for modeling manufacturing processes which add/remove material, and regularity captures mathematically the notion of physical solidity or "homogeneous three-dimensionality".

The four-year period 1974-77 was devoted to a two-pronged development of this approach. One line of work was concentrated on theory; it dealt with such issues as variational modeling (loosely, "tolerancing"), the role and characterization of nominal and variational representation schemes for solids, and the general and algebraic topological foundations of geometric modeling. One important but difficult area was reserved for study in the indefinite future: the characterization of certain mappings (homeomorphisms) on regular sets that may be used to model deformation processes (forging, etc.).

The second line of work was concentrated on the computational implications of object modeling, and especially on a promising representation scheme called Constructive Solid Geometry (CSG). CSG is

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<1> The work described in this report was supported primarily by the National Science Foundation under Grants GI-34274X and APR76-01034.

often dubbed "building block geometry" because it enables one to define complicated solids as "sums" and "differences" of simpler solids which are, at the lowest level, primitive solids such as blocks and cylinders. The results of this work include a tangible embodiment of CSG in the PADL-1 system <2>, a family of algorithms for computing various properties of constructively represented solids (e.g. boundary, "appearance"), a promising "geometric utility function" called Set Membership Classification, and a collection of part survey data which may be used to guide the design of industrially viable geometric modeling systems.

* * *

ACTIVITIES SINCE THE SEPTEMBER 1977 REPORT

Our activities during the past twelve months fall into three broad categories: documentation and dissemination of our research on object modeling, fostering industrial utilization of our object modeling technology, and planning future research aimed at process modeling and planning. Activities in each category are summarized below.

Documentation & Dissemination of Our Object Modeling Research

These activities were distributed over the four categories below. We provide under the first two categories a "roadmap" to guide potential readers through our documentation <3>. Some pre-1977 documents are included for completeness, but various papers in conference proceedings are not cited; acquire our document list <3> for more information.

1) Documentation of Theory

   a) Our view of geometric modeling in the context of mechanical design & manufacturing: TR-1-I (1974) and TM-23. TR-1-I also discusses current (1974) manufacturing proctices from a systems engineering viewpoint.

   b) Mathematical modeling: TM-28 and TM-27 provide mathematical answers to the question, "What is a solid?".

   c) Representation schemes: TM-29* and TM-25 describe and characterize schemes for representing (designating) individual solids. TM-25 focuses on a powerful scheme dubbed Constructive Solid Geometry (CSG).

   d) Representation of variational (tolerancing) information: TM-19.

   e) Computation of geometric properties: general algorithms for evaluating properties of solids represented via CSG are discussed in TM-26*, TM-30, and in portions of TM-25 and TM-27.

2) Documentation of Technology

   a) Technology surveys: TR-1-A (1974) surveys computer graphics, and TR-1-D (1973) surveys numerical controller technology.

   b) Surveys of mechanical parts (to guide the design of systems): TM-21 (1976).

   c) The PADL language (an embodiment of a CSG representation scheme): TM-20 (1974, 1978*).

   d) System, commissioning, and user documentation for the PADL-1.0/n processor, which is a major computer program for translating PADL-1 definitions and producing displays of defined objects: SD-01, 02, 10, 14, 15, 98, 99, and UM-01.

   e) Support software packages which are part of the PADL-1.0/n system but also may be used independently: CRDM-5a, 9, 13b, 14a*.

3) Dissemination of the PADL-1.0/2.8 System

   The dissemination policy is set forth in ADM-01. ADM-02 describes special provisions available to educational institutions that wish to become PADL-1 Distribution Centers.

   At this writing (August 1978) ten copies of the system have been shipped and at least three of the ten have been fully commissioned. We expect to receive between five and ten additional orders before the end of the year. The list of recipients is split about equally between industrial firms and universities, and the list of host computers currently includes PDP-11's.

<2> PADL is an acronym for Part & Assembly Description Language. The PADL-1 system is described in earlier reports presented in this conference series and in other P.A.P. reports cited below and in other conference papers.

<3> See "Documentation" at the end of this report. Starred documents may not become publicly available for two-four months. Some of the cited documents are under review for publication in archival journals.

CDC-6000/7000 machines, IBM-360/370's, an HP-3000, and a PDP-10. The intended uses of the system range from research through engineering education to industrial familiarization. (The PADL-1 system was never intended to be broadly useful in industry; it is primarily a research, teaching, and demonstration tool.)

4) Education

In January of 1978 we presented in Atlanta, by invitation, a 1.5-day Micro-Course on geometric modeling to some seventy member representatives of CAM-I, Inc. In June we offered two Short Courses at the University of Rochester: an intensive five-day course on modeling theory and a two-day course on PADL technology. About sixteen people, mainly from industry, attended the courses. We shall probably offer the Short Courses again, and we shall endeavor to announce them earlier and more widely. No regular university courses on geometric modeling were taught during the past year, but at least one is scheduled for the 1978-79 academic year.

Several M.S. degrees have been awarded for research conducted under the P.A.P.'s auspices. Our current students are prosecuting research which will lead to more M.S. degrees and a few Ph.D. degrees.

*

Industrial Utilization and the PADL-2 Project

An adequate mathematical theory and an exemplary technology are publicly available for modeling completely the nominal and variational geometry of a large class of industrial parts and assemblies. Considerable development remains to be done, of course, but this is properly the province of the vendor and user communities.

We expected in 1975-77 that the vendor community <4> would extend the PADL-1 system's geometric coverage to produce a new generation of industrial geometry systems as soon as we made PADL-1 and its knowledge base available. Consultations with potential vendors in 1977 showed this view to be naive. The following types of barriers were cited: accelerated obsolescence of existing product lines, insufficient resources <5>, and the absence of NC capabilities in the PADL-1 prototype. No vendor, however, questioned the importance of PADL-style technology.

Three other relevant events also transpired in late '77. General Motors launched an in-house project to develop a very powerful modeler using PADL's mathematical principles <6>, the P.A.P. was asked by industrial friends to carry PADL development further, and our internal planning for future research led us to revise and sharpen our views on the role and character of geometric modeling systems. Our current view, which is shared by a growing array of industrial authorities, is summarized in Fig. 1. In essence, a geometric modeling system should contain multiple representations of object geometry and means for creating, editing, accessing, and administering such representations; it should not contain means for USING geometry if one wishes to distinguish a geometric modeler as a distinct (sub)system which may be a component of various larger application systems.

The broad outlines of a collaborative university/industry project, now known as the PADL-2 Project, began to emerge in the fourth quarter of 1977. The central premise: although geometric modeling systems will vary from company to company in regard to input media and output (application) modules, most should be able to share a common "functional core". The major elements of this core will be subsystems for handling multiple representations, accessing procedures, and -- importantly -- internal procedures to insure validity and consistency over the set of representations. Thus the Project is not intended to produce a "final" or directly useable geometric modeling system, but rather a set of compatible software modules from which families of modelers can be built.

The common-core concept dictates the Project's constituency:

-- relatively large companies having the expertise to interface core modules to their existing graphic and data-base systems,

-- vendors of CAD/CAM technology who wish to embed core modules in proprietary systems, and

-- research groups such as the P.A.P. that need powerful modeling facilities for experimental purposes.

<4> By "vendor community" we mean the group of ten-or-so suppliers of mechanically oriented computer graphic systems. Their individual gross sales range from about 5 to 50 M$/year.

<5> Vendors' estimates of the cost of converting PADL-1 into an industrially viable system ranged upward from 1 M$. Some vendors also questioned whether their technical staffs could cope with a technology of PADL's sophistication.

<6> See "Preliminary Design for a Geometric Modeller", by John W. Boyse (GM Research Report GMR-2768, July 1978).

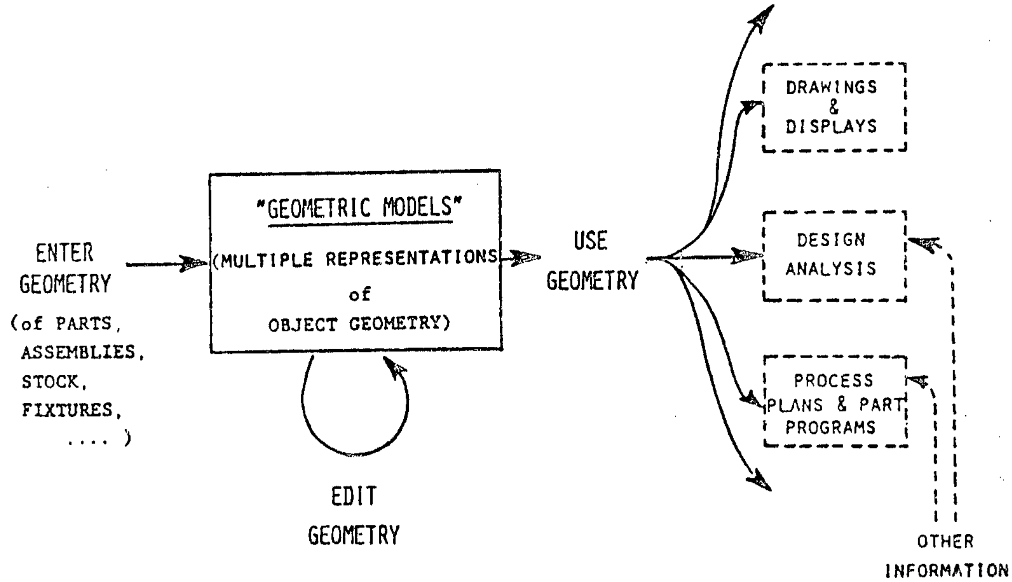

FIGURE 1

A Geometric Modeling System

The constituency suggests that

- -- the Project should be university-led (because the primary expertise lies in the P.A.P.) and its staff should include industrial personnel;
- -- industry should cover some or most of the Project's cost;
- -- a research funding agency should contribute funds because the Project will generate new research tools;
- -- software produced by the Project should be sequestered for a finite period (e.g. one year) after the Project's completion, but made publicly available thereafter under conditions that are only moderately restrictive.

Representatives of potential user companies and vendors were asked in December to determine their companies' potential interest in sponsoring the PADL-2 Project. By April enough favorable responses had been received to justify the preparation of a formal Prospectus to solicit industrial sponsors and a companion Proposal to seek NSF funds. Both documents are currently under review.

The PADL-2 Project, if launched, will address several important technical issues that fall in the grey area between research and system design. We regard it as an activity to be conducted (and staffed) in parallel with the research program discussed below.

*

Planning of New Research on Machining-Process Modeling & Planning

Our work on geometric modeling has yielded a theory and a technology for describing objects, and both contain operators (the motional and regularized set operators) for describing the geometrical aspects of some basic manufacturing phenomena -- specif' ally, positioning (as in material handling and setup for machining), material removal via machining, and collision or interference. Apparently we now have the tools to initiate serious research on the problem of planning automatically the manufacture of conventional parts via conventional machining. We shall summarize the approach we expect to pursue over the next several years.

Fig. 2 presents our conception of a prototypical GENERATIVE PLANNING SYSTEM. Observe the following.

- -- The system's "data environment" is defined by the upper and lower rectangles in Fig. 2; these contain complete geometrical descriptions of an ensemble of parts, stock, machine tool structures, etc., plus technological data relevant to machining processes.
- -- A task is posed to the system by specifying (e.g. by name) a pair of workpieces -- typically a part and its starting stock. Additional task specifications, e.g. schedule and cost constraints, will be added eventually.
- -- The system's output consists of sequential setup instructions to be executed by humans or NC manipulators, and a sequence of NC (machining) part programs to be executed in the various setups. The operations so specified constitute a sequence of transformations that will carry an initial workpiece into a finished workpiece.

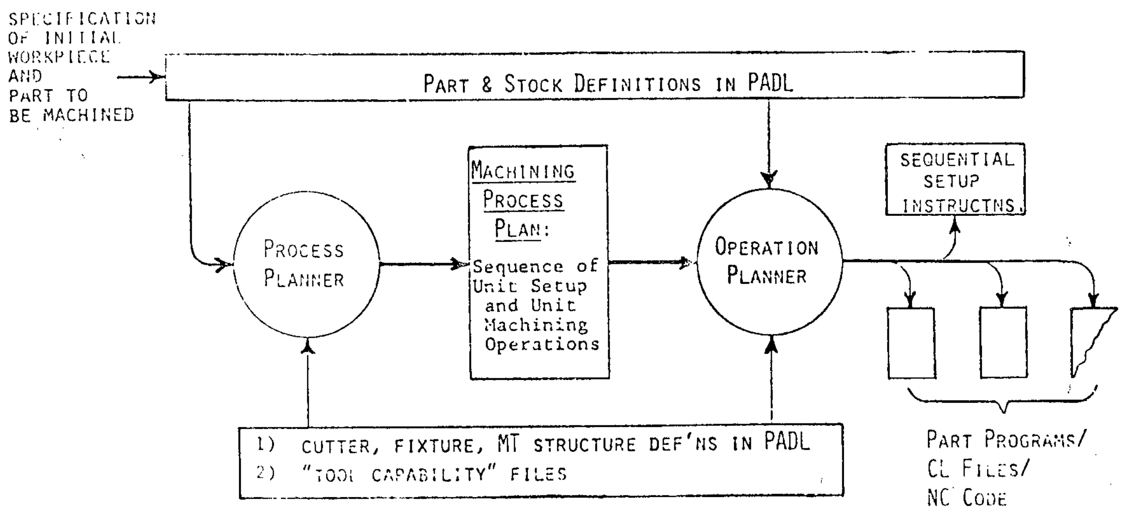

FIGURE 2

A Prototypical Generative Planning System for the Manufacture of Parts by NC Machining

Fig. 2 embodies a central premise: machining-process specifications may be constructed in two stages. The first, high-level stage is Process Planning; it yields plans expressed as sequences of Unit Setup and Unit Machining operations. These have the following flavor.

ROTATE <part> BY <angle> ABOUT <axis>
AFFIX <part> TO <fixture> PER <clamping spec>
BORE <feature> PER <optional spec>
ROUGHMILL <feature> PER <optional spec>

... and so forth, where objects, features of objects, etc., are geometrically specified entities that may be designated by name.

The second, low-level stage is Operation Planning; this expands each unit operation into a series of instructions for NC tools or manipulators. Observe that the two stages of planning in Fig. 2 correspond loosely to process planning and part programming in today's manual-planning world. A second central premise: both types of planning can be done (eventually) by automata.

To bring automatic planning systems closer to realization, we propose to focus our research initially on the design, definition, and conditional implementation of a Machining Process Language (MPL) which will serve as a formal representational medium for machining process plans. It will contain as primitives the two major classes of unit operations cited above, and it may be thought of as a very high level part programming language.

An effective MPL cannot be designed in an ad-hoc manner; both process planning and operation planning must be studied to effect a complexity balance. (If the MPL is too high-level, automatic operation planning becomes very difficult; if it is too low-level, automatic process planning becomes very difficult and/or tedious.) The research issues include modeling of cutter-swept volumes, formal specification of constraints (e.g. accessibility constraints), mathematical characterization of machine tool capabilities, and so forth. We expect to exploit the codification of machining practices done at Purdue by Barash et al., some of the simpler planning methodologies developed by the A.I. community, and of course our own work on geometric modeling and our more recent (and as yet unreported) work on automatic verification of NC tapes.

* * *

OBJECTIVES FOR 1979

Our two major objectives are to launch the research program in process modeling and planning summarized above, and to launch separately the PADL-2 Project if it attracts sufficient support. Specific tasks to be completed during 1979 include a close assessment of our computing requirements and a subsequent enhancement of our computing resources, and a study of the key technical issues involved in the design and implementation of the geometry systems which will be needed two to three years hence to support research in machining-process planning.

* * *

DOCUMENTATION

Reports and memoranda --

TR-1-I:	Discrete Part Manufacturing: Theory & Practice
TR-1-A:	Survey of Computer Graphics
TR-1-D:	Survey of Numerical Controller Technology
TM-19:	Part & Assembly Description Languages I: Dimensioning & Tolerancing
TM-20a:	Part & Assembly Description Languages II: Proposed Specifications for Definitional Facilities in PADL-1.n & Tentative Specifications for Command Facilities
TM-21:	Methodology and Results of an Industrial Part Survey
TM-22:	An Introduction to PADL: Characteristics, Status and Rationale
TM-23:	Geometric Modelling of Mechanical Parts and Processes
TM-25:	Constructive Solid Geometry
TM-27:	Mathematical Foundations of Constructive Solid Geometry: General Topology of Closed Regular Sets
TM-28:	Mathematical Models of Rigid Solid Objects
TM-30:	A Study of Geometric Set-Membership Classification
CRDM-5a:	Users' Guide to STCPAK, A String Package for FORTRAN Programmers
CRDM-9:	Users' Guide to GPAK: A Suite of FORTRAN Subprograms for Computational Geometry & Graphics
CRDM-11:	Users' Guide to Version 22 of the Oregon FLECS/FORTRAN Programming System
CRDM-13b:	High Core Access and Allocation Routines (HICAAR)
SD-01:	The PADL-1.0/n Processor: Overview & System Documentation
SD-02:	Representations in the PADL-1.0/n Processor: Simple Geometric Entities
SD-10:	Representations in the PADL-1.0/n Processor: Boundary Representations & the BFILE/1 System
SD-14:	Representations in the PADL-1.0/n Processor: The Drawing File
SD-15:	Processes in the PADL-1.0/n Processor: The Drawing File Processor
SD-98:	PADL Message Manual
SD-99:	PADL-1.0/2.8 Status & Commissioning Information
UM-01:	PADL Primer
ADM-01:	Dissemination of the PADL-1.0/n Processor
ADM-02:	Guidelines for PADL Distribution Centers

A complete list ("Document List") of our reports and publications is available. It describes the procedure for obtaining documents, provides a brief summary of each item shown above together with a designation of its author(s), page count, and release date, and lists conference papers and other items not shown above. A copy of our Document List may be obtained by writing:

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* * *

CONTACTS

Queries dealing with technical or policy matters should be directed to Professor Voelcker at the address given above. Administrative queries should be addressed to Ms. Peirce.

* * *

DELIVERABLES

The PADL-1 dissemination package is available. Interested parties are advised to order ADM-01 and SD-01 from our list of documents.

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COLLABORATORS

Personnel from the Eastman Kodak Company, General Motors Research Laboratories, Gleason Works, Xerox Corporation, the University of Leeds (U.K.), and New Mexico State University have collaborated in the work reported here.

* * *

COMPUTER-AIDED INJECTION MOLDING SYSTEM

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Sibley School of Mechanical & Aerospace Engineering

Professor C. Cohen
School of Chemical Engineering

Cornell University

PROGRAM OBJECTIVE - The use of polymeric materials has been steadily increasing in recent years, replacing metals for the purpose of cost reduction and energy conservation. Injection molding is the most important process for producing simple as well as intricate parts to close tolerance for numerous engineering applications. However, like some other types of manufacturing, the injection-molding process remains somewhat of an art, depending heavily on experience.

The main objective of the present program is to build up a scientific base for this important manufacturing process. Our approach is to treat the problem as an integrated system of mold design, mold making, and process control. The interdependence of mold design and process control has not been investigated due to the lack of knowledge of the dynamic behavior of the process. The present program is aimed at obtaining a fundamental understanding of the process dynamics so that a rational strategy of mold design and process control can be evolved. An integrated computer program is being developed which incorporates description of mold geometry, numerical simulation of mold-filling, and prediction of optimum process conditions.

PROGRAM ACHIEVEMENT -

First Period (Progress Report #1, January 1975): A critical review of the literature on simulation of the mold-filling process was carried out during this 6-month period. Some fundamental aspects of the normal-stress differences and the pressure dependence of viscosity were also briefly examined.

Second Period (Progress Report #2, September 1975): Work was accomplished in three major areas: materials characterization, the experimental program for one-dimensional radial and channel flow, and refinement of simulation models. The first material, Monsanto's Lustran ABSQ714, was independently characterized for its shear viscosity as a function of shear rate and temperature using both capillary and orthogonal rheometers. The resulting data were curve-fitted with a Gillespie-type constitutive equation which was used in the simulation program. Extensive mold-filling experiments on a fully instrumented mold with disk and strip cavities were carried out. The disk-filling data were analyzed by plotting the axial total-stress difference (as measured by a pressure transducer) versus the injection rate. The simulation results were found to agree fairly well with the experimental data even with the number of assumptions involved. The effect of viscous heating in a capillary rheometer was also examined and evaluated.

Third Period (Progress Report #3, October 1976): The major effort was concentrated on an experimental and numerical program for one- and two-dimensional-flow mold configurations. The numerical scheme employed in solving the finite-difference equations was improved to reduce computational time and increase accuracy. Both ABS and polypropylene were used in the experiments; the constitutive equation for polypropylene was modified to account for its crystallinity. Good agreement between the predicted injection pressures and the experimental data was achieved for filling a center-gated disk, an end-gated strip, and a center-gated cup mold with both ABS and polypropylene. The two-dimensional-flow program also successfully predicted the advancing melt front in an off-center-gated rectangular plate cavity. The predicted pressures at four different locations were found to agree remarkably well with the measured pressure traces, particularly with the one nearest the gate. These results were applied to predicting (as a first approximation) the injection pressure and clamp force required for molding an automobile door trim panel and a refrigerator liner. Reasonably successful predictions were achieved for comparing alternative mold designs. Other work carried out in this period included studies of melt-temperature measurement, pressure dependence of viscosity, and implementation of the TIPS-1 CAD system.

Fourth Period (Progress Report #4, September 1977): An experimental and simulation program of general two-dimensional flow in a cavity with inserts and multi-gating was carried out. The investigation included the formation of "weld line" (the meeting of two melt fronts). A combined finite-element/finite-difference numerical scheme was developed and used for simulation of flow around inserts and filling cavities with more than one gate. Extensive experiments were performed with two materials (ABS and polypropylene) involving a two-gated rectangular cavity with removable inserts. A large number of short shots was taken to study the flow-front advancement and the weld-line formation. The concept of using a graphical method (design charts) for predicting injection pressure and clamp force (as a first approximation) was developed and further improved. Reasonable results were obtained when compared with experimental data and a more exact numerical simulation for the filling of an off-center-gated rectangular plate cavity. The method was applied to analyzing the molding of an automobile door trim panel with varying number of gates and gate locations. Work in this period also included further development of a finite-element method for analyzing the entrance-flow problem. In addition, a prototype integrated CAD program was developed incorporating the description of part geometry in TIPS-1 language, mold-filling analysis including automatic mesh generation for FEM, production of engineering drawings, and graphical representation of results from engineering analysis.

RESEARCH RESULTS SINCE THE SEPTEMBER 1977 REPORT -

(A) Cavity-Filling Simulation. Our finite-element/finite-difference program for simulating the filling of thin cavities of fairly arbitrary planar geometry has been significantly extended by implementing a scheme which employs the streamfunction (ψ) and temperature (T), rather than pressure (p) and temperature as primary computational variables. The formulation involving the streamfunction has been found to be much more stable, allowing successive over-relaxation (in contrast to under-relaxation, as in the pressure formulation) and, hence, faster convergence. In addition, the derived velocities are less sensitive to inaccuracies in ψ than p, being proportional to $|\nabla\psi|$ as compared with $|\nabla p|^{1/n}$ (where n is the power law index which, for our materials, is such that $1/n \simeq 3$).

Our ψ-T formulation has been applied to our earlier experimental results involving a two-gated rectangular mold with intentionally unbalanced flow through the two gates. A typical short-shot sequence with polypropylene is shown in Figure 1. This is to be compared with corresponding predictions for the advancing melt front, as shown in Figure 2. A detailed comparison with experiment is given in Figure 3, where the curves are the pressure traces obtained from Dynisco transducers (positions indicated in Figure 2) whereas the symbols denote corresponding predictions. In particular, it is noted that the first abrupt rise in trace 1 (at t ≃ 1.5 sec) corresponds to when the left end of cavity gets completely filled; the final sharp rise coincides with the formation of the weldline and the consequent tendency to block the flow from the left gate. The agreement between the data and predictions is seen to be quite striking. On a more refined level, though, it is noted, e.g., that transducer #1 predictions are low whereas #2 predictions are high. In turn, this can be attributed to an underprediction of the flow rate from gate #1 (left one, in Figure 2) with a consequent overprediction from gate #2. This is substantiated by Figure 4, which plots the total volume of melt from gate #2 versus that from #1 (obtained by measuring the respective areas of the short shots) and compares this with corresponding results based upon the time integral of the predicted flow rates through the two gates. Due to the rather excellent predictions for the cavity-pressure levels (howbeit, displaced in time), it seems reasonable to suspect that the noticeable inaccuracy in the relative flow rates through the two gates is due to a rather crude modelling of the pressure losses in the delivery system (in terms of an isothermal power-law fluid). This will be an area of future investigation.

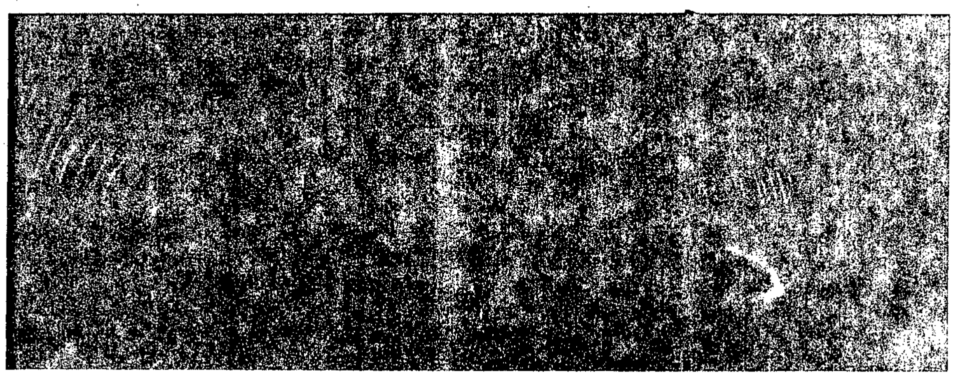


Figure 1. Short-shot sequence for two-gated rectangular plate; polypropylene.

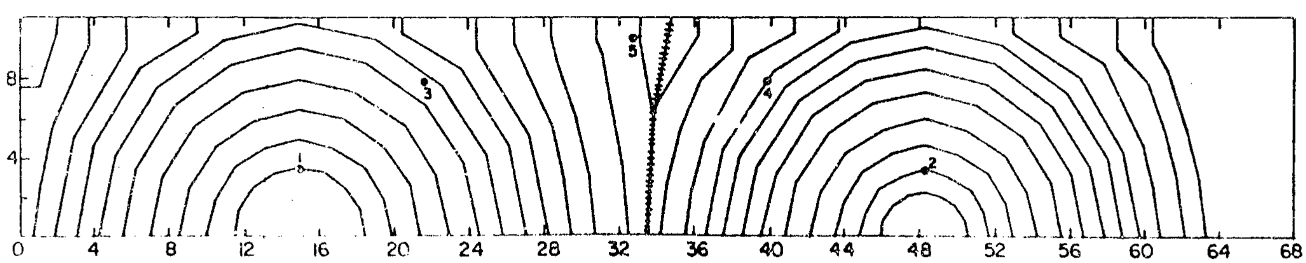


Figure 2. Predictions for advancing melt front; ++++++++ : weld line.

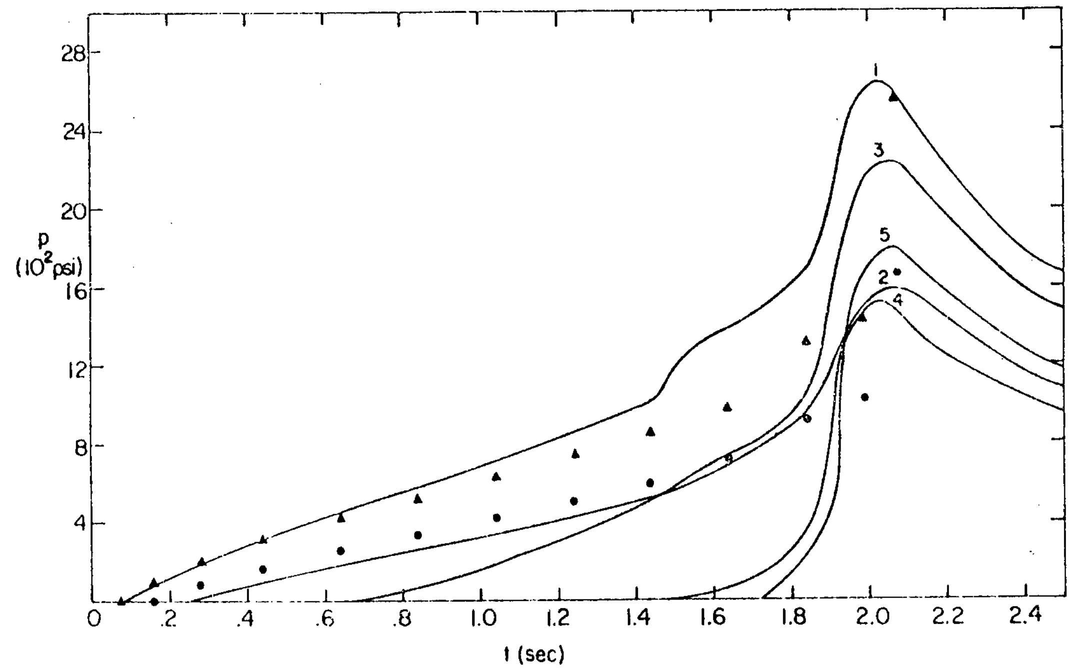


Figure 3. Pressure traces according to measurements (curves) and predictions (symbols).

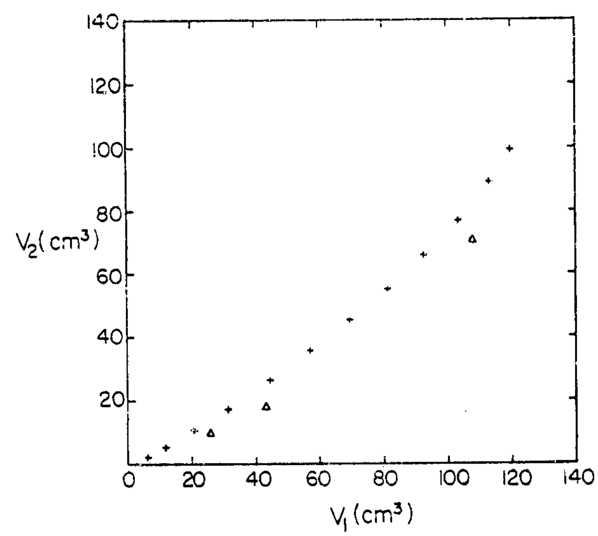
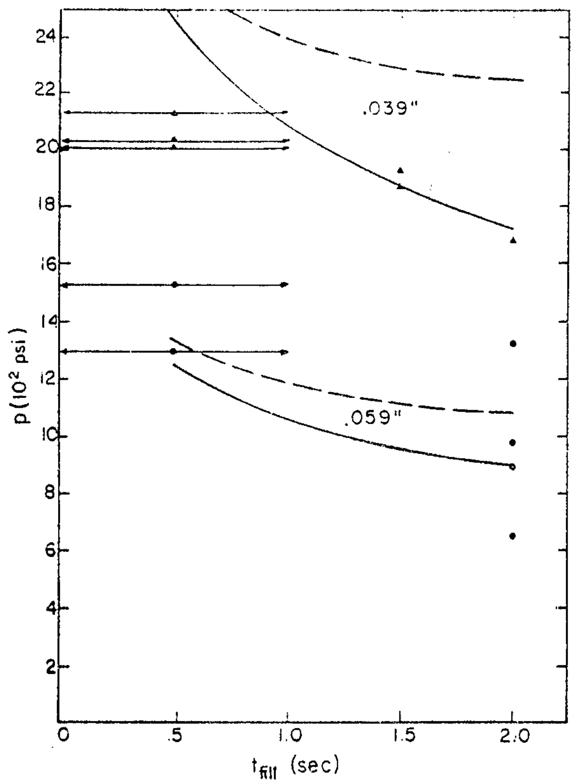


Figure 4. Relative volume through two gates according to short-shot measurements (Δ) and predictions (+).

(B) Cavity Filling with Asymmetric Cooling. An interesting industrial molding problem was recently brought to our attention in which one surface of the cavity is Bakelite and the other steel. Due to the significantly different thermal properties of these two materials, the respective wall temperatures are quite different; in particular, the steel surface should be very close to the coolant temperature whereas the Bakelite surface should be almost midway between the coolant and inlet-melt temperatures. A further complication is that the polymeric material being employed (polypropylene) is semi-crystalline and the gap thickness of interest is extremely small; accordingly, the cooling effect can be quite substantial which, in turn, implies that the crystallization could have a significant influence on the effective viscosity of the material during filling.

Figure 5 shows data obtained by a company's development staff on a 3" x 5" test mold having two thicknesses, as indicated, together with our own predictions. The mold was center-gated with the pressure being measured at 1.2 inches from the center along the shorter axis. Our predictions are based upon treating the mold as an equivalent disk with due modifications to account for asymmetric wall conditions. Although there is considerable scatter in the data, it does appear that the solid curves more closely represent the data, particularly in the more critical .039"-gap case. In turn, this suggests that the crystallization temperature employed in generating the dashed curves (390°K, as obtained from standard DTA-DSC measurements at a cooling rate of 10°C/min) may be unrealistically high when applied to the injection-molding filling process in which the relevant cooling rates are higher by a factor of 100 or more. This matter will receive further consideration in a more carefully controlled experiment presently being designed by our project.

Figure 5. Pressure-transducer reading versus fill time for 3" x 5" plate mold with thickness of .039" and .059"; solid (dashed) curves are predictions in which crystallization effect upon viscosity has been omitted (retained); data points are for plate thicknesses of .039" (▲) and .059" (●).



(C) Fountain Effect Problem. This problem relates to the detailed flow behavior in the vicinity of the advancing melt-air interface. Our present cavity-filling simulation treats the interface as being flat in the gap-wise direction with any motion in that direction being neglected. Although this simplification has been found adequate for predicting pressure drops and flow rates, a more accurate description of the interface is required for addressing the problem of orientation (hence, anisotropy, etc.) in the final molded part. The importance of the interface in this regard stems from the fact that the outer layer of the molded part is formed by molecules which pass through the melt front before being deposited on the mold wall. Experimental investigations in the literature suggest high orientation in the skin layer, the cause of which has been attributed to this melt-front region. To date, however, no completely satisfactory analysis or flow description has been obtained.

Our own effort in this regard starts with the simplest idealization of the problem, namely the creeping flow of an isothermal Newtonian fluid with the interface advancing at a uniform speed (U) through a channel. Schematically, the situation is as shown in Figure 6, as seen from a frame fixed to the interface: far upstream the flow is fully developed (Poiseuille) together with the superimposed uniform speed of interface; along the wall, the no-slip condition requires that the fluid move at speed U to the left whereas evident symmetry conditions apply along the centerline. Lastly, conditions along the interface require the vanishing of the normal velocity and the normal and tangential tractions (neglecting surface tension and the viscosity of medium ahead of interface). The solution technique will later be extended to treat the real case involving non-Newtonian and non-isothermal effects.

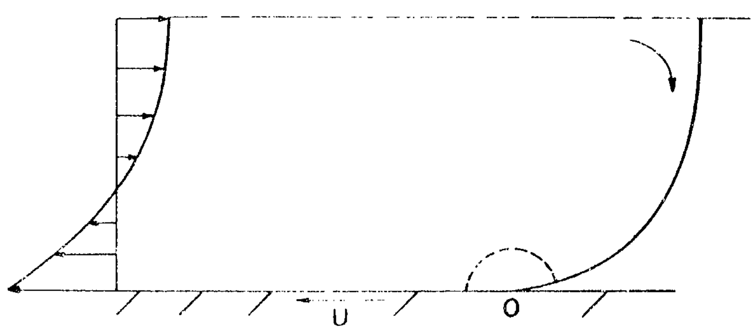
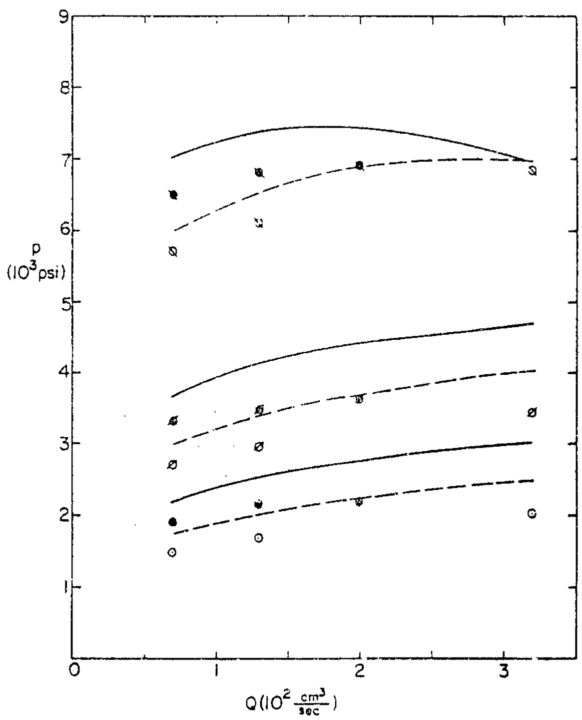


Figure 6. Schematic for "fountain-effect" problem.

Our present attempt at solving this problem involves the use of a finite-element formulation which uses the velocity components and pressure as primary computational variables and handles the traction conditions along the interface as natural boundary conditions. Although the field equations are linear, the overall problem is non-linear as a result of the unknown interface and the boundary conditions along the same. The problem is further aggravated by the presence of a stress singularity at the attachment point, O. Although we have obtained a local solution about the latter point and used this as the basis for a special element, calculations to date have not been completely satisfactory. In particular, derived quantities from the finite-element calculation have not been consistent with the known local behavior in the vicinity of the special element. The comparison seems to cast some doubt on the validity of the local singular solution. However, we have recently obtained the next-order term in the singular expansion and can now conclude that the size and functional form of the special element should be satisfactory. Accordingly, we are in the process of improving the numerical accuracy through refining the finite-element configuration in the region surrounding the special element and by employing curved elements along the interface.

(D) Runner Experiment. An independent investigation has been made into predicting and measuring the pressure drop in cold runners. The intent is to determine the adequacy of a power-law-fluid model having an exponential-decay temperature dependence. Such a model, when applied to circular runners with axial conduction and radial convection omitted, leads to a numerical simulation which can be represented in terms of four non-dimensional parameters. As a result, such a solution lends itself to graphical representation for easy use.

Some preliminary experimental results, obtained on an industrial injection-molding machine, are shown in Figures 7, 8, and 9, together with corresponding predictions based upon the above model. The results in Figures 7 and 8 represent the overall pressure drop for polypropylene and ABS, respectively, in round runners of 18" length. The comparison is somewhat reassuring although further experimental results will be required in order to establish the repeatability and reliability of the measurements. A more detailed comparison is shown in Figure 9 for polypropylene in half-round and trapezoidal runners, the non-circular cross-section having been replaced in the simulation by a circle of the same area. In this case, due to the flatness of at least one side of the cross-section, it has been possible to use flush-mounted pressure transducers along the length of the runners; in particular, transducers 2, 3, 4, and 5 were located at distances of 3-1/4", 7", 10-3/4" and 14-1/2", respectively, from the runner inlet with the overall runner length again being 18" and transducer 1 being located in the reservoir as in Figure 7 and 8. The agreement between the data and predictions is again fairly reasonable. In particular, the results in Figure 9 indicate essentially no difference between the half-round and trapezoidal cross-sections. Further, comparison of the results for transducer 1 with those for 2-5 suggest a rather significant entry pressure drop which, however, is not suggested by the results in Figures 7 and 8. Although the present results are somewhat encouraging, further experimental work will be in order.



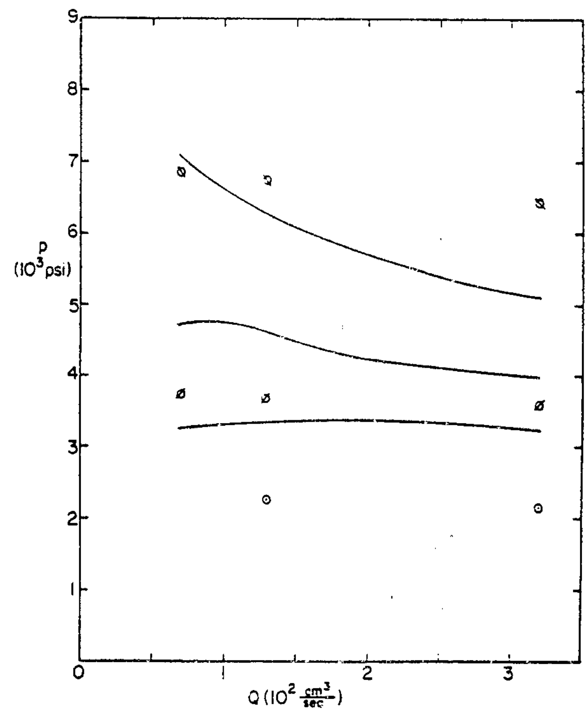
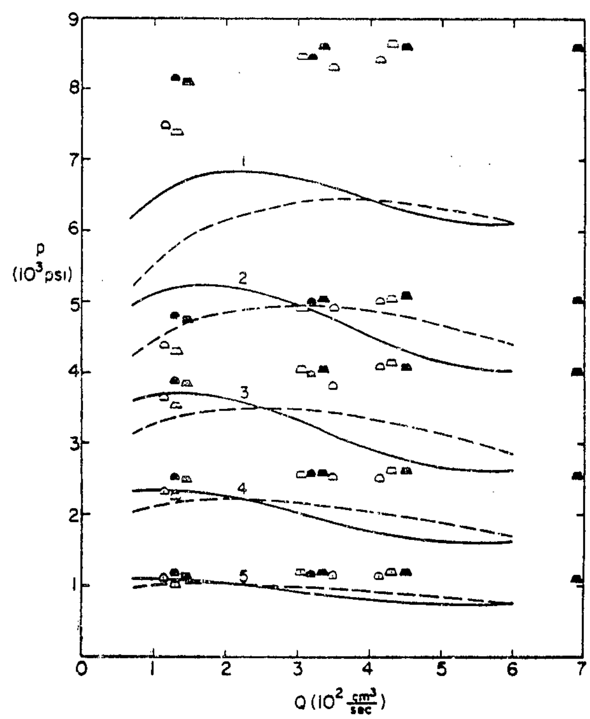


Figure 7. (above) Overall pressure drop versus flow rate for polypropylene in round cold runners for various melt temperatures (T) and diameters (D); data: ● (T = 400°F, D = 1/2"), O (480°F, 1/2"), ⌀ (400°F, 3/8"), Ø (480°F, 3/8"), ◙ (400°F, 1/4"), ⍉ (480°F, 1/4"); predictions: solid curves (400°F), dashed curves (480°F).

Figure 8. (above right) Same as Figure 7 but for ABS at 500°F.

Figure 9. (right) Pressure versus flow rate at transducers 1-5 for polypropylene in half-round (3/8" diameter) and trapezoidal (of same area) cold runners; data: solid symbols (T = 410°F), open symbols (490°F); predictions: solid curves (410°F), dashed curves (490°F).



(E) New Exploratory Work and Mold Design Program. Some exploratory work has been initiated with regard to the mechanical properties of molded parts which are known to be affected by the mold-filling process. The final goal is to predict (hence, to "control" or "manipulate", if possible) the mechanical properties of the part in terms of its molecular orientation when the mold-filling process is prescribed. We have started the development of a semi-empirical model for the molecular orientation in flowing melts. The simplest of the bead-spring models (the dumbbell) is being considered as a starting point in hopes of making use of the vast amount of information available on single-molecule conformation. Aside from the basic modelling of orientation, we have started to measure birefringence as an indirect measure of the molecular orientation. After a preliminary study, we choose to use the classical polariscopy technique to obtain birefringence values as opposed to the holographic interferometry method which would generate more information in one step but which might be more difficult to interpret. In view of the limitation of the optical method which is only applicable to transparent materials, we are also examining the effect of flow-induced orientation on mechanical properties of parts which are not transparent. Standard tensile tests have been carried out on a number of specimens cut out from molded ABS disks, parallel as well as perpendicular to the flow direction. Preliminary results indicate that the tensile yield stress has not been changed significantly by flow rate, direction of flow, or the distance from the gate. On the other hand, appreciable differences in total elongation have been noticed between the specimens which are parallel to the flow versus those which are perpendicular to the flow.

The effects of elongation and visco-elasticity upon the flow through junctures and gates are being addressed in a combined numerical and experimental study which has recently begun in cooperation with one of our industrial collaborators. The possibility of incorporating the "Marrucci equation" as a reasonably accurate general constitutive equation is being explored.

The effort in building up the mold-design program has concentrated on implementing the current TIPS-based program in a mini-computer environment. The mold-filling program for disk and strip cavities has been successfully employed on a PDP11/40 system which, unfortunately, is unable to handle the TIPS-1 program. Efforts are being made to implement the new TIPS which has recently been developed for minicomputer systems. In addition, a standard mold-component file and a cooling-line design program will be incorporated in preparation for the mold design via interactive computer graphics.

OBJECTIVES FOR THE NEXT YEAR -

- Further improve numerical solution techniques for mold-filling with complex geometries.
- Complete the studies on runner design and mold-filling with asymmetric cooling.
- Extend simulation program to include visco-elastic effects in junctures and gates.
- Conduct studies of orientation problems from basic as well as phenomenological viewpoints.
- Continue to develop a prototype of the computer-aided mold-design program in interactive mode via computer graphics.
- Explore the possibility of establishing a Users' Group as a mechanism for dissemination of research results for potential industrial applications.

DOCUMENTATION -

(A) Progress Reports:	No. 1,	published in	January 1975 -	76 pages
	No. 2,	"	" September 1975 -	151 pages
	No. 3,	"	" October 1976 -	164 pages
	No. 4,	"	" September 1977 -	129 pages

(B) Journal and Conference Papers:

1. "An Experimental Study and Simulation of Disk Filling by Injection Molding", by J. F. Stevenson, C. A. Hieber, K. K. Wang, and A. Galskoy, Paper No. 35, 46th Annual Meeting, Society of Rheology, October 1975.
2. "Viscous Heating in a Capillary Rheometer", by C. A. Hieber, Paper No. 6a, ibid.
3. "Computer-Aided Injection Molding System", by K. K. Wang and C. A. Hieber, Proc. of the Int. Conf. on Prod. Eng'g., Tokyo, February 1976, pp. 308-313.
4. "A Composite Leveque-Graetz Solution to the Brinkman Problem", by C. A. Hieber, Letters in Heat & Mass Transfer, Vol. 3, 1976, pp. 117-124.
5. "An Experimental Study and Simulation of Disk Filling by Injection Molding", by J. F. Stevenson et al, 34th ANTEC, SPE, April 1976, pp. 282-288.
6. "Fill That Mold — A Quick Way to Estimate Pressure and Clamp Force", by J. F. Stevenson, R. Hauptfleisch, and C. A. Hieber, Plastics Eng., Dec. 1976, pp. 34-37.
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COLLABORATORS -

The Black & Decker Mfg. Co., Cincinnati Milacron, Inc., Eastman Kodak Co., Ford Motor Co., General Electric Co., Rogers Corp. and Xerox Corp.

DESIGN FOR ECONOMIC MANUFACTURE

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PROGRAM OBJECTIVE - The design of parts and products so that they can be manufactured economically has been the subject of discussion for many years and its importance as a means of reducing manufacturing costs and increasing productivity has long been recognized. Yet this aspect of manufacturing technology has not been developed to a degree that allows it to be presented in a form suitable for use by the average design engineer with little experience. The possible savings in manufacturing costs that can be brought about at the design stage are rarely studied in depth and yet this is the area which probably holds the greatest potential for significant reductions in manufacturing costs.

The object of the research program being conducted at the University of Massachusetts is to collect and present, in a convenient way, information that is normally possessed by an experienced design engineer. Although some new information is likely to be developed, this is not the main purpose of the research. Hopefully the data can be assembled in the form of design handbooks and computer software.

PROGRAM ACHIEVEMENT AND RESEARCH RESULTS - This research program was started in September, 1977 and the progress made during the previous ten months will be discussed under three main activities: (i) identification of candidate process and material combinations; (ii) detailed design for economic manufacture; (iii) computer-aided design for manufacture.

Identification of Candidate Process and Material Combinations - It is important to introduce considerations of manufacturing economy in the earliest stages of the design process. In particular, preconceptions about the part geometry must not result in the unwarranted elimination of potential manufacturing methods without proper consideration. To avoid this problem, a coding system is being developed to help the designer identify the most likely process and material combinations for a part before its geometry is fixed.

The coding system deals with those characteristics of a part which are most important in deciding process and material combinations. Some of the characteristics which will probably be included in the coding system are: (1) Batch Size - Some manufacturing processes such as die casting or cold forging are only economic when a large batch size is to be produced and the cost of expensive tooling can be spread over a large number of parts. When a small batch size is to be produced it will be more economic to produce parts by processes such as sand casting and machining which require a smaller investment in specialized tooling. Thus the batch size is an important consideration in process choice; (2) Bulk - Part size and weight can play an important part in process selection. Many processes such as die casting, powder compaction and cold forging are limited as to the size of the parts that can be produced because of equipment limitations; (3) Geometry - The geometry of the part is obviously important in process selection and this aspect of the code is one of the most difficult problems to be solved. However, it should be realized that, at the stage the code is to be used, part geometry will still be relatively flexible. Thus, in ascertaining geometric constraints, it is necessary to find out if particular geometrical configurations are possible. For example, a given part could be conceived of as basically prismatic, opening up the possibility of making it by extrusion, rolling, drawing, etc. The same part could also be conceived of as axisymmetric with the possibility of making it by turning, swaging, spinning, etc. The coding system must reflect both of these possibilities. The final part geometry will eventually be decided by the relative economics of the various processes and associated materials; (4) Criteria of Excellence - The criteria by which a part is to be judged vary according to its function and the type of device in which it is to be used. For example, a part in a machine tool may have to combine high stiffness with low cost, while a part in an aircraft may have to combine high strength with low mass. This difference in criteria of excellence can result in completely different process and material selections for parts with otherwise similar characteristics. Thus the machine tool part might best be cast from grey iron while the aircraft part might best be forged from titanium alloy; (5) Loading - The type and duration of loading to which the part is subjected will also influence process and material selection. For example, making a part from an injection molded thermoplastic may be acceptable if loading is light and of short duration but high loads over long periods could make this choice unacceptable due to creep deflection; (6) Temperature - The sensitivity of the mechanical properties to temperature varies from one material to another. Thus for a part operating near room temperature an injection molded thermoplastic might be more economic than a steel pressing while at higher temperatures the injection molded thermoplastic would not be a viable alternative; (7) Other Characteristics - A large number of other characteristics also influence material and process selection. For example, considerations of wear, corrosion, thermal or electric conductivity, etc. can all be important in particular applications. However, it is believed that these do not usually play an important role and that they can be handled through an auxilliary coding system at a later stage in the research.

Once a coding system has been devised, each code number will be matched with a small number (say three or four) process and material combinations. This can be achieved by treating each characteristic separately and eliminating unsuitable or unlikely process and material combinations. If too many possibilities emerge from this process then the coding system will be expanded to cover additional characteristics.

The next stage will be to try the system with some existing parts to see if it correctly generates the manufacturing process and material actually used. If this does not happen, then the reason will be sought and the code adjusted as necessary.

Design of Parts and Products for Economic Manufacture - When considering a particular manufacturing sequence, it is important for the designer to be aware of the various design features that can affect manufacturing costs. In the present research program three principal processes are initially being studied: (i) handling of component parts; (ii) assembly; and (iii) machining.

(i) Design of Component Parts for Ease of Handling - The handling of parts in manufacturing and assembly plants represents a considerable portion of the manufacturing costs. The design features that can affect handling times have been studied with a view to developing a coding system which can be used to evaluate a particular design and draw attention to those features which will present handling problems.

An initial study of major Time and Motion Study systems revealed that the following major design features can affect the times required for handling during manual assembly operations: flexibility, severe tangling, symmetry, size, thickness and the weight of the part. Other minor features which affect the handling times can be grouped within one category. These variables are: the roughness of the part surface or other features requiring careful handling (such as fragility, sharp corners, slipperiness, etc.) and the nesting of parts. All the above are candidate features for the coding system.

For example, Fig. 1 shows the results of an experiment designed to study the effect of symmetry on the time required to handle the part during manual assembly. For a particular part, which is randomly presented, and which is to be placed in a given orientation, it is possible to estimate the total angle of rotation required to orient the part to its desired position. The effect of this angle on handling times is shown in Fig. 1 for hexagonal, square and cylindrical parts 50 mm long and 25 mm in their major cross-sectional dimension. It can be seen that all parts can be grouped into four categories of symmetry with approximately 330 ms of time penalty between each category; and that the handling times vary as much as 1 s depending on the symmetry of the part. It will be appreciated that, in assembly operations, reductions in the total assembly time by 1 s per part can have significant effects on economics and productivity.

Similar experimental results have been obtained for the effects of the size, thickness and flexibility of parts and based on these results it has been found possible to produce a two-digit classification or coding system for the design of parts for ease of handling.

(ii) Design for Ease of Assembly - Some of the factors in addition to part orientation and handling, which can increase the ease with which a product can be assembled are: (i) reduction in the number of parts; (ii) provision of a suitable base component; (iii) assembly in layer fashion from above along a vertical axis; (iv) elimination of lengthy fastening techniques; (v) design for ease of locating or aligning by the provision of chamfers, pilots, etc. For example, the design of chamfers to facilitate assembly has received the attention of many investigators in the past. Figure 2 shows the results of some experiments conducted to examine the effect of chamfers in the common process of inserting a peg into a hole. It can be seen that the manual insertion time depends largely on the clearance between the peg and hole but can be significantly reduced for small clearances by the provision of suitable chamfers. Further work indicated that the use of an optimum curved chamfer can reduce insertion times to the minimum value shown in Fig. 2 for all clearances. This chamfer is a body of constant width (Fig. 3) and ensures that, during assembly, no more than two contact points can arise between the peg and the hole, hence eliminating the possibility of jamming during the early stages of insertion.

Figure 4 shows an example of the redesign of a box and lid assembly. The lid has been redesigned to eliminate asymmetry about the vertical axis and is self locating. The screws have been produced with chamfered pilots and are also self locating. The effects of various design changes were tested. The results, presented in Table I, show that the manual assembly time can be reduced from 28 s to 14 s by using self located/aligned screws and lid. The change of the symmetry of the lid had no measurable effect on the assembly time.

(iii) Design for Machining - The machining costs for a particular component can be broken down into two parts: (i) the costs incurred while the component is gripped in the machine tool, these will be termed the productive costs; (ii) the costs incurred due to handling the component, including loading and unloading and transferring the component from one machine tool to another. These costs will be termed the non-productive costs and can form a large proportion of the total costs.

The objectives of this portion of the research are to study the component design features which affect these costs and combine the results in a suitable coding system which can be used to evaluate a particular design. Actually the coding system devised by Optiz[1] is initially being considered because it contains many of the features of interest in the present work.

At present an attempt is being made to produce an approximate method for estimating the productive costs involved in machining the various surfaces on a workpiece. It is being assumed that, for comparison purposes, machining is being conducted under optimum (minimum cost) conditions. Figure 5 shows the machining cost per machined area for a single point boring process for a range of workpiece hardness values. In order to use this graph it is necessary to know the feed, f, employed and the machine and operator costs, M. The feed f can be obtained from Fig. 6 from a knowledge of the surface roughness or

tolerance desired and the type of cutting tool used. The machine and operator rate M can be obtained from Fig. 7 for typical machines and for a variety of operator wage rates. Hopefully the summarizing of cost data in this way will provide a means of quickly estimating the productive costs involved in machining a particular component and these costs, when added to the non-productive costs will indicate which design features should be reconsidered in order to improve the manufacturability of the design. By way of example, the use of Figs. 5 and 6 indicated that the cost of boring a surface having a roughness of 1 μm will involved productive costs approximately twice those for a surface of roughness 5 μm when a round nosed tool is employed.

Research is also being conducted on the design of parts for non-traditional machining processes. Non-traditional machining processes are often defined as those machining processes that are either emerging or have not been used extensively in the past. There are currently about twenty-six non-traditional machining methods, and these can be broken down into four basic categories; mechanical, electrical, thermal, and chemical.

Presently, the non-traditional methods most often used are electrical discharge machining (EDM), electrochemical machining (ECM), chemical machining (CHM), photo-chemical machining (PCM), ultrasonic machining (USM), electron beam machining (EBM), and laser beam machining (LBM).

Over the past year two preliminary coding systems have been devised, one for EDM, which is a thermal process, and one for ECM, which is an electrical process. In both cases, a six digit coding system was used where the first digit codes the workpiece size and the tolerances; the second, third, and fourth digits account for the machine workpiece shape and features; the fifth digit codes the workpiece material; while the sixth digit accounts for the surface roughness. The coding systems were designed so that a part which has a higher six digit number costs more to machine than a part that has a smaller six digit code.

Computer-Aided Design for Manufacture - This phase of the research is focusing on the implementation of an extended, computer assisted code generation program for manufacturable parts and automated assemblies. Already, a three digit, part shape coding program has been established on the PDP 11/34 computer system. Presently, the system has very limited graphic capability. Thus, to simplify and accelerate the coding procedure, while a designer answers shape or assembly characterizing questions asked by the computer, the computer will display corresponding graphic examples of suggested responses. This scheme appears promising with the incorporation of PADL (part and assembly description language). The PADL language developed at the University of Rochester, is a computer graphics program which can construct and fully dimension simple mechanical parts and assemblies on the display screen.

PROGRAM OBJECTIVES - During the next ten months it is anticipated that working classification and coding systems will be developed for: (i) the identification of candidate process and material combinations; (ii) design for ease of handling and assembly. Research will continue on design for non-traditional machining and computer-aided design for manufacture. Finally, research will commence on design for forging

DOCUMENTATION - Four detailed progress reports and five research papers are now in various stages of preparation. A video tape lecture by G. Boothroyd on design for economic manufacture was produced by M.I.T./N.S.F.

COLLABORATORS - During the progress of this research it is intended to cooperate with the University of Salford and the Cranfield Institute of Technology. At the University of Salford work is progressing on the classification and coding of small assemblies for automatic assembly(2); a study which is being closely coordinated with the program at the University of Massachusetts. Efforts are being made to cooperate in a similar manner with the research program at the Cranfield Institute of Technology.

An industrial collaborative effort has also been established with the Xerox Corporation.

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TABLE 1 TOTAL MANUAL ASSEMBLY TIME FOR FASTENING A LID ONTO A BOX

No.	Design of Lid			Design of Screws					manual assembly time (s)
	lid is self-located/aligned and does not require orientation	lid is not self-located and aligned		screw is self-located/aligned (with pilot)		screw is not self-located/aligned			
		lid does not require orientation	lid requires orientation (0° or 90° rotation)	screw is inserted into the hole by hand	screw head was engaged with the screw driver before insertion	short screw does not have to be started by hand (5 threads)		long screw has to be started by hand (13 threads)	
						not started by hand	started by hand		
1	x			x					14.04 ± 1.45
2	x				x				18.00 ± 2.78
3		x		x					19.66 ± 2.46
4			x	x					18.03 ± 1.44
5	x					x			23.27 ± 8.32
6		x				x			24.23 ± 5.63
7			x			x			23.63 ± 3.73
8	x						x		27.57 ± 8.32
9		x						x	29.51 ± 1.67

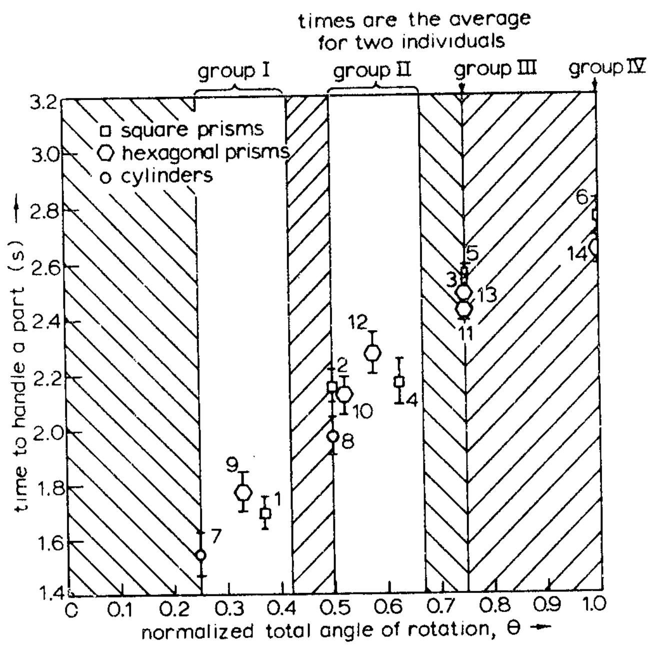

FIGURE 1 Relationship Between the Total Angle of Rotation and the Time Required to Orient a Part

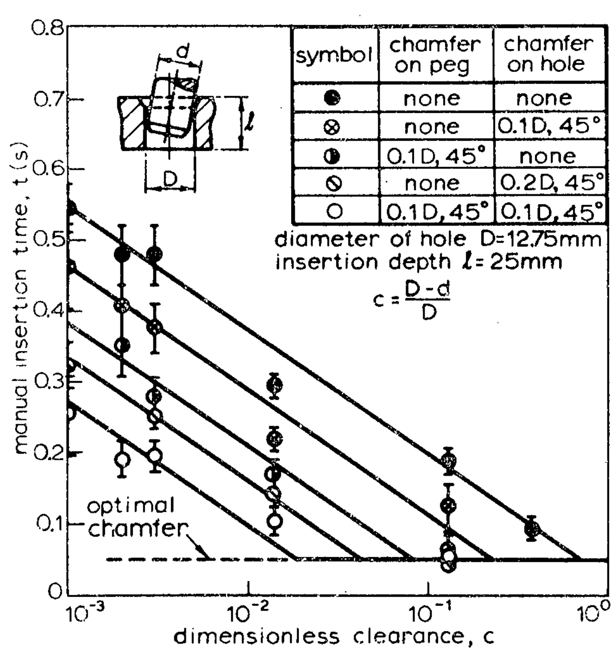

FIGURE 2 Effect of Clearance and Chamfer Design on Manual Insertion Times

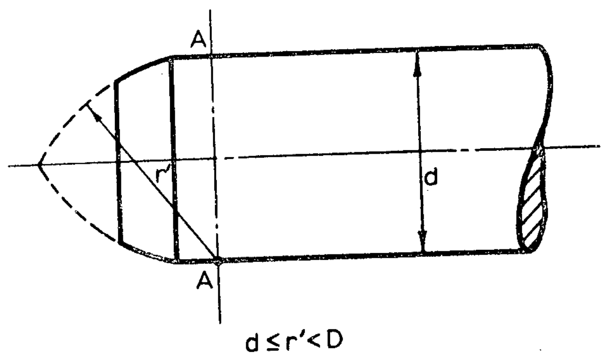

FIGURE 3 Optimum Chamfer Design

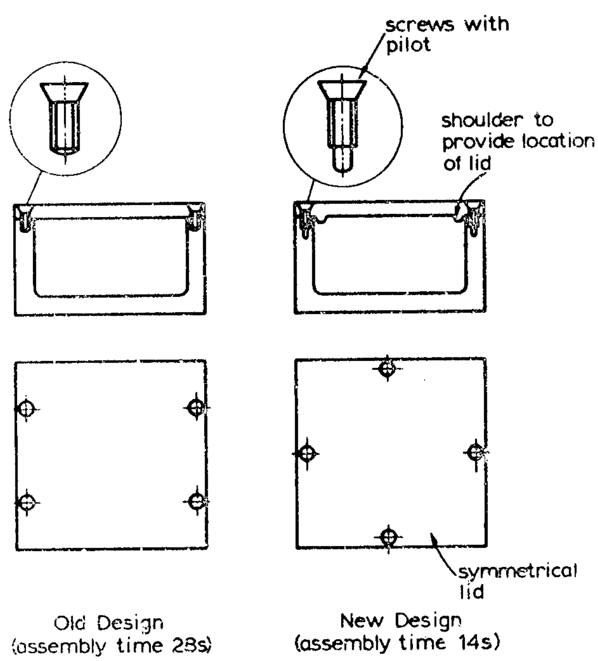

FIGURE 4 Example of Redesign for Assembly

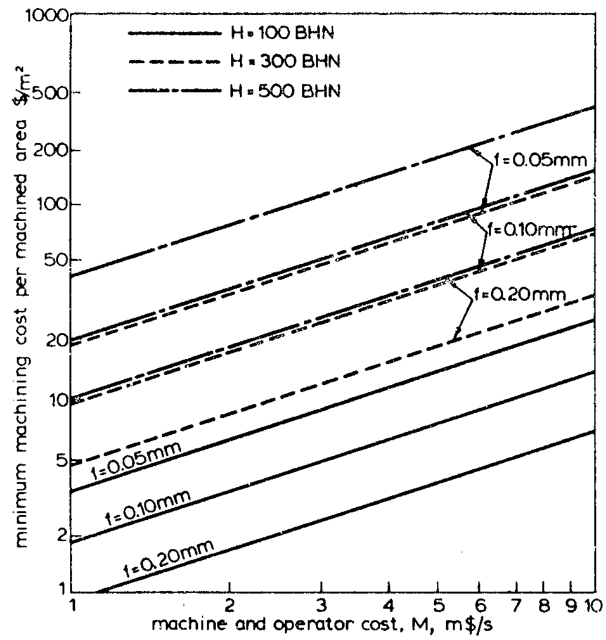

FIGURE 5 Minimum Machining Cost Per Machined Area for Boring (f - modified feed)

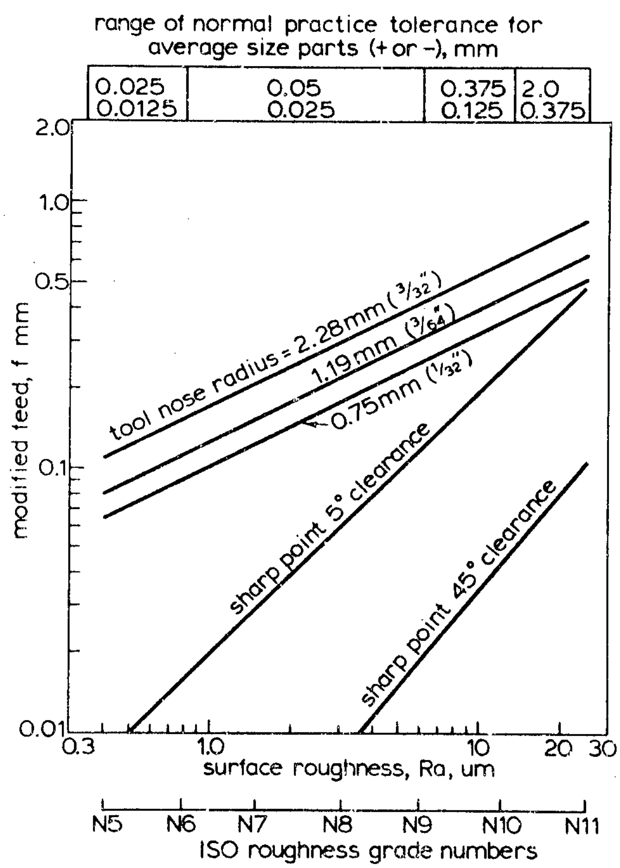

FIGURE 6 Relationship Between Feed and Surface Finish or Tolerance with BHN 125-450

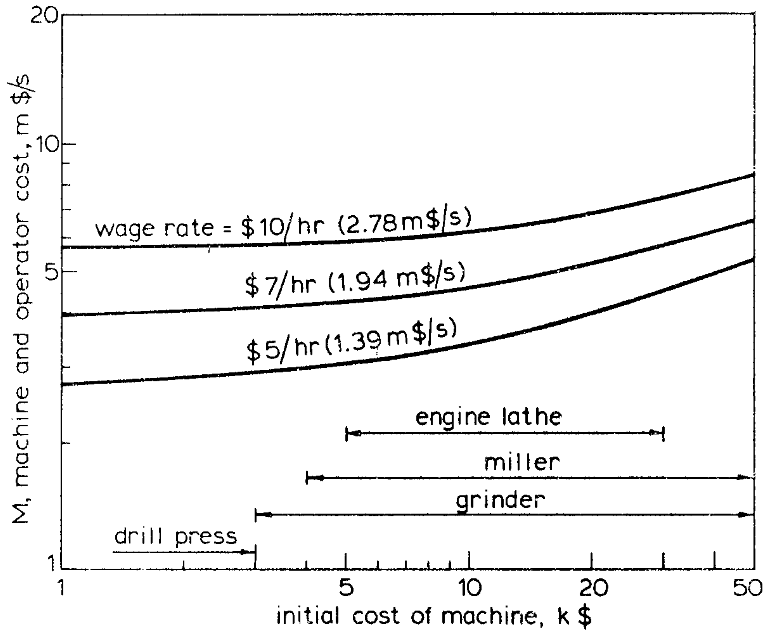

FIGURE 7 Total Machine Rates for 100 Percent Overhead on Both Operator and Machine (Amortization Period = 5 years - 1 shift)

OPTIMAL PLANNING OF COMPUTERIZED MANUFACTURING SYSTEMS (CMS)

NSF GRANT NO. APR74 15256

A PROGRESS REPORT
by

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PROGRAM OBJECTIVES - The basic problem to which the project addresses itself is the insufficient utilization of numerically controlled (NC) machine tools in the U.S. metalworking industry.

Although first introduced commercially in 1955, NC machine tools as yet account for less than three percent of the total operating stock. The main reason for the slow introduction of NC is the inability of current production management methods to fully utilize the potential of this new technology. Analysis of the activities involved in keeping an NC machine tool cutting metal for its entire running time shows that human involvement in the actual production process is the primary slowing down factor. The solution to this problem, suggested several years ago by a number of independent studies is to automate as many as possible of the production functions in the same manner as the NC cutting process. Out of this has evolved the concept of the Computer Integrated Manufacturing System, which represents an automatic, computerized job shop section.

Such system has the versatility ("flexibility") of a group of general purpose machine tools, and is comprised of several NC machine tools linked by automatic handling devices, with in-process automatic storage, automatic gauging and workpiece positioning. The operation of the system is controlled by an on-line computer. The system is adaptable to a wide range of parts to be machined, and the control strategy is such as to achieve maximum utilization. It has been estimated that the productivity of such systems can be twice that of stand alone NC machine tools. In the last six years over forty such systems have been installed in the U.S., East Germany, West Germany, Russia, Czechoslovakia and Japan. Of these, four are in the U.S. and about thirty in Japan, but the American systems are much more complex than the Japanese. However, Japan has embarked on a much more ambitious program of building a prototype of an "unmanned" factory for machinery parts. An estimate based on the projected growth of NC equipment installations indicates that approximately 100 Computer Integrated (or Computerized) Manufacturing Systems should be built yearly for the American industry by 1985**. It is postulated that wider introduction of such systems will only take place if a rational methodology is developed for their optimal design and operation.

A study of 4½ year duration aimed at the development of such methodology has been proposed and a request for funding submitted to the National Science Foundation. Support for two years was granted on May 1, 1975, under Grant No. APR74 15256. The study is being conducted by faculty and graduate research assistants at Purdue University in collaboration with the Caterpillar Tractor Company, the White-Sundstrand Machine Tool Company, and the Ingersoll-Rand Company. It is concerned with parts other than shafts, discs and gears, i.e., with box, bracket, plate and "irregular" shapes.

The originally proposed study has four major components, identified by analysis of steps through which a system design should ideally progress. The steps in system design are shown in the flow diagram in Figure 1, and major components of the study are listed alongside on the right. The diagram shown is greatly simplified and does not include feedback loops existing in the process. Detailed diagram is presented in Report No. 1 of the project. Not shown in the diagram but performed at all stages in economic analysis of all decisions made.

The major research components are:

1. Unit Machining Operations - A unit machining operation is an intersection of two sets. One set describes all features of the surface to be machined, the second contains processes with which such surfaces can be produced in general. The intersection contains all processes and their parameters for producing the specific surface in the first set. As an example, one can take a cylindrical hole. A code developed for the purpose, describes all parameters of the hole as stipulated by the designer, namely material of the part in which the hole is made, diameter and length of the hole, accuracy and surface finish. Set of "hole making process" includes drilling with twist, spade and gun drills, reaming, boring, lapping, etc. Intersection of the two sets provides the process or processes which can produce the hole to specifications, and also the machining parameters (feeds, speeds, axial force, torque) for each stage

* Complete listing of Project Staff is given at the end of this report.

** This assumption can also be supported by interpretation of a recent SME publication "Delphi Forecast of Manufacturing Technology - Manufacturing Systems Material Removal."

in each process. Similar surface process specifications are developed for plane surface, slots, recesses, etc.

System Design Logic	Major Research Components
Select a group of parts belonging to the same family. Decision based on production needs	
↓	
Determine machining content of each part and of typical, desired batch of parts	1. Unit Machining Operations
↓	
Determine primary system functional elements, including all machine tool elements	2. System Functional Elements
↓	
Compose various system configurations, including various handling subsystems	3. Reliability Analysis
↓	
Simulate operation of all variants to test their overall performance	4. Computer Modeling
↓	
"Best" system design is identified. Optimum operating rules for this system are set.	

Figure 1

2. System Functional Elements - Output of section (1) includes data on feeds, speeds, forces, torques and accuracy to be available in system machine tool elements, primarily spindles. Orientation of machined surfaces vectors gives the number of controlled axes required. Parts dimensions determine machine table size. These data are used to identify existing machine tools suitable for inclusion in the system and such which have to be specially built from the identified building blocks.

Using data on identified functional elements and machining content in a desired production batch, total number of machine tools in the system is derived. With this information, a number of system configurations are composed, each with one or more material handling systems for parts, and for both parts and tools. The composition is "manual", where designer experience, imagination and intuition are the only limitation.

3. Reliability Analysis of Computerized Manufacturing Systems (CMS) - Each element in the system, be it a cutting tool, switch in a machine tool or material handling system, bearing, integrated circuit, etc., etc. has a probability of failure. It is known from theory of reliability that such probability is only in part dependent upon age, i.e., accumulated operating time. A manufacturing system is a very complex, multi-component object and its reliability must be assessed prior to construction. The most "unreliable" element in the system is the cutting tool, but even the most reliable components--the machine tools--sometimes fail, usually because of chain of events started by human error. Both mathematical models of system reliability and alternative solutions (e.g., use of long lasting but expensive borazon tools instead of carbide tools) have to be produced and analyzed.

4. Computer Modeling of Computerized Manufacturing Systems (CMS) - Tools developed by the first three components of the proposed study will enable one to compose many variants of manufacturing systems intended to perform the same task--the machining of a defined range of items to given specifications. To facilitate such composition and to permit the selection of the optimal variant or variants meeting certain other desired criteria, computer simulation will be employed. GASP IV will be used as the basis for a simulation program consisting of various subroutines specific to manufacturing system features. System simulation is a representation of system real time operation but on a vastly contracted time scale. The same system can be "run" in a number of different ways, each following its own procedure. The computer simulation of a CMS aids the system designer in the detailed specification of components and procedures

for the proposed system. Such simulation will also provide the means for developing and testing production scheduling algorithms to be employed in actual operating CMS.

PROGRAM ACHIEVEMENT THROUGH SEPTEMBER 1977

In the period of May 1975 to September 1977 the research, after preliminary studies conducted at the Caterpillar Tractor Company and White-Sundstrand Machine Tool plants, was pursued primarily in the areas of Unit Machining Operations, Scheduling Theory, Mathematical Modeling, and Simulation.

1. Unit Machining Operations - Over one-hundred parts of the Caterpillar production program were identified as belonging to the class for which computerized manufacturing systems in the context of the project can be employed. About one third have been analyzed in detail and several hundred machined holes, slots, grooves, recesses, and bounded and unbounded flat surface were fully described and classified.

Machining technologies employed for machining all above types of surfaces both on the DNC line and elsewhere at the Caterpillar plant in Peoria were studied in detail and sufficient information has been collected to identify comparable technologies and parameters in technical literature which describes the better industrial practice in this field. Considerable amount of such literature has been accumulated, representing American, European and Soviet machining experience.

The underlying philosophy of the Unit Machining Operations (UMO) system is to represent in a computer-readable form all features ("attributes") of the machined surfaces which the design engineer enters in the detailed part drawings. Only then can the automatic process selection and planning segment of the UMO system identify the process(es), tools and machine tools best suited for the job. It was established that 51 attributes are needed to fully describe a hole (multidiameter, threaded, etc.) 32--a slot, 33-- a surface. A few of the attributes, however, are related to process technology rather than surface features. List of attributes for a slot is given in Figure 2. (Attributes for a hole were listed in our summary in the Proceedings of the Fifth Grantees' Conference).

ATRIB(1)	SURFACE IDENTIFICATION NUMBER
ATRIB(2)	SURFACE(HOLE,SLOT,PLANE)
ATRIB(3)	SLOT TYPE
ATRIB(4)	PRECAST INDICATOR
ATRIB(5)	MAXIMUM STOCK REMOVAL (DEPTH OF CASTING SKIN)
ATRIB(6)	WORKPIECE MATERIAL TYPE
ATRIB(7)	BRINELL HARDNESS OF WORKPIECE MATERIAL
ATRIB(8)	DIRECTIONAL VECTOR
ATRIB(9)	BLIND SLOT INDICATOR
ATRIB(10)	SIDE SURFACE FINISH
ATRIB(11)	BOTTOM SURFACE FINISH
ATRIB(12)	BOTTOM SLOT INDICATOR
ATRIB(13)	RADIUS (LENGTH) OR ANGLE FOR BOTTOM INDICATOR
ATRIB(14)	LENGTH OF SLOT
ATRIB(15)	DEPTH OF SLOT
ATRIB(16)	MAXIMUM DEPTH OF SLOT
ATRIB(17)	MINIMUM DEPTH OF SLOT
ATRIB(18)	DEPTH OF Y OR T AT THE BOTTOM OF THE SLOT
ATRIB(19)	WIDTH AT TOP OF SLOT
ATRIB(20)	ANGLE FOR DOVETAIL OR Y
ATRIB(21)	WIDTH AT BOTTOM OF T OR Y SLOT
ATRIB(22)	PARALLELISM-FORM GEOMETRY
ATRIB(23)	FLATNESS-FORM GEOMETRY
ATRIB(24)	ANGULARITY-FORM GEOMETRY
ATRIB(25)	PROFILE OF A LINE-FORM GEOMETRY
ATRIB(26)	PROFILE OF A SURFACE-FORM GEOMETRY
ATRIB(27)	MAXIMUM END RADIUS FOR RECTANGULAR SLOT
ATRIB(28)	SPECIFIED CUTTER DIAMETER
ATRIB(29)	REFERENCE SURFACE FLAG
ATRIB(30)	NUMBER OF SLOTS TO BE PRODUCED PER TOOL
ATRIB(31)	ACCESS SIDE AND LIMITATION
ATRIB(32)	SURFACE NUMBER LOCATED IN THIS SLOT

Figure 2

A computer program was written to represent the surfaces in a coded form (program COFORM - COding FOR Maching), using mnemonics to simplify its use. In many cases certain attributes (for example tolerance or surface finish) are repeated on several surfaces in the same job, so the program has default capability. A preset value of attribute will be assumed if it is not stated. (An example of coding is given in Progress Report prepared for the Fourth Grantees' Conference.)

Extensive study of machinability data and equations was conducted to provide basis for the process selection program for unit machining operations. Based on results of this study, a computer program was written which receives input in the COFORM format and provides automatic process selection with speeds and feeds for machining surfaces in steel and cast iron. The program which has been called APPAS (Automated Process Planning And Selection) takes into account not only obvious information such as material and dimension, but also the accuracy and finish of the surface to be produced. In many cases not only alternative processes but also machining parameters for different tool materials are part of program output. Detailed tool life equations are built into the program, and any desired life value can be input.

Normally life of 20 minutes was taken for drills, 30 for end mills, 45 for reamers, and 60 for boring tools, but the program can also compute machining parameters for minimum time or for a specified number of surfaces to be made per one tool life period.

2. Optimization of Multitool Setups - The concept of Unit Machining Operations by definition applies to single-tool operations. There are, however, instances when tool "clusters" can be used to advantage in an integrated manufacturing system. Optimization of the work of such clusters poses major mathematical difficulties. Although exact solution has been obtained using geometric programming*, it requires a very large computer if the number of tools in the cluster is greater than four. An approximate optimization method has therefore been developed [12] which can be applied to multispindle synchronous machines (e.g., Bullard-type lathes) and tool clusters, with up to 20 spindles or tools. The method and the computer program are presented in Report No. 8.

3. Scheduling Theory - A very extensive evaluation of the technical literature in scheduling viewed in the context of the real life problems for computerized manufacturing problems, revealed little that was directly useful. Considering the immense amount of published work in this area, we were quite surprised at this outcome. Perhaps this research will ultimately contribute more to scheduling theory, by revealing new problems, than the reverse.

A naive view of the problems might suggest that a static optimization procedure could be used. That is, an "optimal" fixed sequence of operations could be determined for some planning horizon, and then carried out without concern for variations from the plan. After all, the operations are controlled by a computer according to rigid parts programs which are of completely predictable duration. However, our experience with real systems clearly indicated the folly of such a notion. Machine breakdowns, traffic congestion, and various kinds of minor interruptions and irregularities occur with such frequency that no fixed plan can be considered optimal for more than a moment. Dynamic scheduling procedures which somehow utilize the most current information about system status seem to be necessary.

An experimental investigation of a number of heuristic methods for loading and scheduling the Caterpillar DNC system was conducted, using the detailed simulation which was developed in the first year of the project. Many possible combinations of rules were tested. Results were surprising in the sense that they did not conform to what we would expect from reading previous studies in the literature. There were many ways to achieve significantly higher production from the Caterpillar system than that which was actually in use.

4. Mathematical Model of a Computerized Manufacturing System - During the early phases of our study of existing systems, it became apparent that internal congestion played an important role in determining the productive capacity of a system. Accordingly, a methematical model which treats the system as a network of queues was developed. We call this model CAN-Q.

Briefly, the model represents the system as a set of workstations (machines, inspection positions, etc.) and a transporter mechanism. A fixed number of workpieces circulate throughout the system in accordance with prescribed routing probabilities, queueing when necessary at individual stations, being processed for random durations at the stations they visit, and eventually reaching a final load/unload station. At this time, the finished workpiece is immediately replaced by a raw casting. The parameters of the model consist of the set of routing probabilities, the mean processing times for each station, the number of servers at each station, the mean transport time, the number of carriers, and the fixed number of workpieces in the system.

These few parameters, along with some assumptions which will be discussed more fully, permit one to calculate an exact equilibrium probability distribution over all possible states of the network. From this, one can go on to find machine utilizations, average queue lenghts, the production rate of the system, the mean production time, and so on. The form of the model is such that these computations can be performed very efficiently, despite the immense number of possible network states.

Although the assumptions which were made for mathematical convenience (e.g., negative exponentially distributed processing times) appeared to be grossly unrealistic, the model was found to provide surprisingly accurate results. It could not, of course, provide information about transient effects, operating policy variations, and a number of other detailed effects. For these, simulation is a necessary tool. However, the steady-state mean performance measures produced by the model are adequate both in terms of nature and quality for most decisions related to the design of the physical system.

Several versions of CAN-Q were programmed. Full scale versions are available in FORTRAN and BASIC. Reduced versions have been successfully implemented on the Texas Instruments SR-52 and SR-59, and on the Hewlett-Packard HP-67 and HP-97 programmable calculators.

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* Batra, J. L. and Barash, M. M., "Computer-Aided Planning of Optimal Machining Operations for Multiple-Tool Setups, etc." Report No. 49, Purdue Laboratory for Applied Industrial Control, Jan. 72.

5. Simulation of Computerized Manufacturing Systems - The operation of the Sundstrand-built CMS installed at Caterpillar was observed over an extensive period of time. In addition, Purdue personnel had extensive discussions with the designers of the system. With the understanding gained, a detailed simulation program, called CATLINE, was developed and subjected to verification and validation procedures. This program was used as a basis for a computer experiment to evaluate the effect of material flow scheduling strategies and of the system's physical configuration. The CATLINE program and the results of the simulation experiment have been presented on several occasions to the management and engineering personnel at Caterpillar and Sundstrand. The results of the experiment were used along with other results from the CAN-Q model, and with Caterpillar's engineering design judgment, to modify the CMS operating procedures and physical configuration. These changes have so far improved the productivity of the system by about seventeen percent.

A more general-purpose CMS simulator, named GCMS, was designed and coded, again in the FORTRAN/GASP IV framework. The objectives for this development were to provide a simulation tool with a much more robust modeling capability than the CATLINE simulation model. For example, the capability is present to represent different material handling systems such as conveyor, unidirectional carts on ellipsoidal tracks, or bidirectional carts on one track. Capabilities are also provided for representing malfunction of machines, carts or conveyors, and tracks. Various recovery procedures from these malfunctions can also be tested by the GCMS user.

6. Developments in Queueing Models - The project supports the development of some new theory in the area of queueing processes that are relevant to CMS. A new queueing model was developed for the M/G/1 queue, in which m types of "customers" are served on the first-come, first-served basis [Project Report No. 2]. This type of queue may model certain automatic tool changing procedures. A more recent paper [Neuts - Project Report No. 9] investigates the effect of a certain type of decision rule for making use of idle time created, for example, by adaptive control on the machine tools. Although the theory is as yet limited to a single machine, it does provide explicit numerical solutions.

7. Extension of Work into Other Systems - A student spent the summer of 1977 collecting data at Ingersoll-Rand Company plant in Roanoke, Virginia where a system of entirely different type than the Caterpillar system is in operation.

RESEARCH RESULTS SINCE THE SEPTEMBER 1977 REPORT

Presented below are research results obtained in the period of September 1977 to August 1978.

1. Unit Machining Operations - The COFORM and APPAS programs were refined to remove nonstandard features and so to enhance their future expansion and portability. In particular, the "Holes" section of COFORM was rewritten in the University of Minnesota Fortran version.

2. Scheduling and Loading Problems - As related in earlier reports, we have distinguished two problems of a scheduling nature which are critical determinants of the performance of any CMS. (This leaves aside the question of which part types are most appropriately produced on a CMS. Though certainly an important and non-trivial problem, we do not consider this a scheduling problem.) Given that a group of parts must be produced, each according to its own production quantity and technological requirements, and recognizing that tool magazines are not large enough to accept simultaneously all of the tools required for all of the part types, which parts should be loaded into the system and how should the required tools be allocated? We call this the loading problem. The second problem, which we call the scheduling problem, has to do with how to make the decisions in real time about routing of active parts to vacant machines so as to minimize congestion, maximize production, and so forth. Although these two problems are intimately related, the time frame in which they must be considered separates them. That is, some solution to the loading problem must be given before the scheduling problem can even be formulated.

With respect to the loading problem, we have managed to formulate the constraints as mathematical expressions. They are non-linear and integer, because of such factors as common tools for different operations. However, we have found ways to transform these constraints into equivalent ones which are linear and continuous. With a suitable linear objective function, the loading problem could be solved by a linear programming algorithm. The difficulty we face at the present is knowing which of several possibilities is the best objective function. We expect to resolve this issue in the near future.

The scheduling problem appears to be unsolvable in anything like a rigorous manner. Quite early in our research, we identified the problem as one belonging to a class of "provably difficult" combinatorial problems, for which no practical algorithm has yet been devised. The consensus of expert opinion is that it will eventually be shown that no practical algorithm can ever be developed for these problems.

At the last grantees' meeting, we reported on some results from a simulation study of heuristic scheduling methods. The ones we tried are quite simple and certainly practical possibilities for real systems. Some of the results were quite surprising, which indicates the importance of conducting such investigations. Our present belief is that no general conclusions about "best" scheduling policies are possible. Rather, it appears that the quality of performance obtained from different policies will depend upon particularities of system design, part processing, and so forth. As a general procuedure, therefore, the selection of scheduling policies for a new system should be made in the light of information obtained from a simulation study of that particular system.

A few general design principles for operating systems can be stated, such as "preserve your options for as long as possible," and "base decisions on the most current information available." However, these principles are more helpful in avoiding bad procedures than they are in selecting particularly good ones. They are still a great many possible variations for which little advance guidance can be offered. We know that even educated intuition is generally unreliable when it comes to guessing the effects of changes in scheduling policies.

3. Mathematical Model of CMS - The CAN-Q model entailed a number of simplifying assumptions which were so patently unrealistic that no reasonable person would expect to obtain very accurate results from it. To our considerable surprise, the model consistently produced results which were within a few percent of what we got from detailed simulations. The quality of results was so startling that a theoretical explanation seemed necessary. Although a complete explanation is still lacking, we have succeeded in obtaining a partial explanation. Apparently the model is a great deal more robust than it appears to be at first glance. Nearly all of the assumptions can be weakened without affecting the answers produced. For example, we know that virtually any kind of part routing structure will give the same results as the simple one used in the original model. Negative exponential service time distributions, which were originally postulated and are clearly unrealistic seem to affect the results only through the means. In other words, other distributions having the same means give the same results.

In addition to the theoretical work, we have accumulated over the past year quite a bit of corroborative empirical evidence that the model does indeed work. It may be some years before we fully understand why, but in the meantime there is little doubt remaining that the model is safe to use.

Since the last report, the programs implementing the model have undergone considerable revision to make them easier to understand and use. We have a version for the Texas Instruments SR-59 calculator with printer, which can handle small systems quite effectively. For large systems, running time becomes a nuisance even though storage capacity is not a problem. The FORTRAN version is now in a form suitable for commercial use. That is, all of the difficult theory has been made invisible to the user, simple instructions have been written, the output has been formated for easy understanding, and so forth. The program has two acceptable input format options and several output options.

In response to requests, the CAN-Q program has been supplied to, and is now in use by, about a dozen major companies. Several universities have also requested the program for research purposes.

A new and important extension to the capabilities of CAN-Q occurred in the past year when we developed expressions for first and second partial derivatives of the performance measures with respect to the input variables. This extension will permit us to make use of gradient search techniques to optimize the performance. At present, we do this manually: run the program, observe the results, alter the parameters in a direction that will improve performance, and repeat.

One byproduct of the development of partial derivatives was a realization that some earlier work on product mix optimization was in error. It can be shown that only in special cases is it desirable to attempt to achieve equal utilization of the machines in a CMS. Indeed, it is not at all obvious how to allocate work so as to achieve maximum output, even in the absence of practical constraints. This fact complicates some of our work on the loading problem mentioned earlier.

Additional work is now underway linking CAN-Q to economic and reliability analysis of computerized manufacturing systems. There are no important theoretical problems here; it is simply a matter of deciding what kinds of analysis are most useful to industry.

4. Simulation of Computerized Manufacturing Systems - The investigation of more general-purpose simulation procedures has proceeded in two directions, namely (1) the testing of the GCMS simulator and (2) the use of the Q-GERT modeling language. Both of these simulation methodologies are being made comparable by focusing their application on two existing flexible manufacturing systems. One of these systems is the conveyorized CMS built by Sundstrand for Ingersoll-Rand. The other existing system was built by Kearney and Trecker for Rockwell. Both systems differ substantially from the Caterpillar system which has already been modeled by the GCMS program.

Simulation Using GCMS - The application of the GCMS simulator to the Ingersoll-Rand system was relatively straightforward. GCMS facilities to model a conveyor loop, on-and-off-shuttles between the conveyor and machines work-tables, decision points to identify full queues to machines, and default rules for controlling part flow were applied in modeling the Ingersoll-Rand system. Actual performance data was collected at the plant for a three day operation. Each day was simulated separately ignoring machine breakdown but using the actual parts production schedule and process plans. Evaluation of this exercise included two main aspects. First, the direct application of GCMS to model such a conveyor type system did not require any program changes or extensions. Second, performance measures obtained by the simulation (particularly, the total time required for daily production, production rate, and average machine utilization) corresponded well to the actual measures after considering the machine breakdown effects. Further applications of the GCMS model in this case study included simulating increased daily production schedules, revised part mix, i.e., less part types per day, and different relative part quantity requirements and revised machine assignment, i.e., different process routing. In all cases the simulation results showed logical and anticipated changes in the performance measures, further indicating the simulator validity.

In order to accurately model the K & T Rockwell line via GCMS, it has been necessary to augment the twenty basic subroutines of GCMS with user-written programs for introducing parts into the system and for moving carts. These programs will be made available to future users of GCMS as an option. In more detail, they include for example the introduction of parts on a "metered" basis so that only a fixed number of parts enter the system on a per-hour basis. This option is most useful to the system designer in the early stages of detailed design. Parts may also be entered on a "desired production level" basis whenever another part is completed and leaves the system. The options for material handling systems include the previously mentioned representation of conveyorized systems, and, for carts, the selection of either the nearest idle cart for part pickup or the selection of cart with nearest destination. The newer developments for cart movement include "pushing" idle carts out of the way and improved procedures for handling blocking and unblocking of carts in unidirectional systems with converging and diverging paths. The simulation results for the K & T Rockwell line (as well as for another small prototype K & T system) were compared to simulation data on the same systems provided by Kearney and Trecker. Comparison of output statistics as well as program traces for both programs showed similar results. The small discrepancies which do exist seem to be attributable for the most part to differences in the details of part introduction and cart movement algorithms.

Our efforts in applying GCMS have revealed a major shortcoming of large programs of this type. That is, the provision of modeled-system data to the computer has been shown to be a tedious and time-consuming process considerably subject to error even on the part of experienced GCMS users. In order to improve access by the designer-user to this general-purpose program and to other programs of this type, we are beginning work on a simulation data-base manager where this effort is described in some more detail below.

Simulation Using Q-GERT - Another effort to model and simulate the Ingersoll-Rand CMS was made using Q-GERT, an established, high level network simulation language [R1]. The model, designated IRHMC [18], is expressed in a network-node notation rather than the specialized CMS specifications in GCMS. The IRHMC model was developed with a variety of user functions to study several fundamental design and control issues related to a CMS. These issues include:

a) The Part Mix Problem: Given part production requirements which parts should be introduced into the system in the same work-day? Analysis with 14 part-types vs. 8 part-types vs. 2 part-types simultaneously in the system (with adjusted quantity requirements) revealed that drastic reduction in the variety of part types is inefficient for this system, apparently because it reduces the balancing effect of different part requirements. On the other hand, in this example it was found that higher part-mix variety leads to better machine utilization and production rate only up to a point.

b) The Part Flow Problem: Given a part-type mix how should individual parts be sequenced into the system? The analysis included variety of part introduction rules in controlling initial part entry (into the empty system), general part entry (into a fully loaded system), and the allocation of parts to machines once they are inside the system. Differences on the order of 10% in various performance measures between initial part entry rules were found and indicate that the issue of initial part entry to a CMS cannot be ignored. In the general entry case, a rule which gives entry priority to part-types with a higher ratio of parts completed to parts required was found better than another rule which gave higher priority to part-types with higher difference between parts completed and parts required. In the part-to-machine allocation the analyses showed advantage to a ratio rule (Production Remaining/Time Remaining in the Day) in five out of six rule combinations.

c) The Process Selection Problem: Given alternative process plans in the CMS for a part-type, which particular one should be selected for an individual part in order to satisfy the system objective? In the analysis processes were assigned to parts prior to entry to the system based on a dynamic rule. Improvements in production rates using the dynamic selection compared to fixed processes were found in the range from 1% to 15% with an average of 7%. Further investigation is planned in this area. Additional details about the above analyses can be found in [19].

A Q-GERT version was made of Solberg's network analysis model, CAN-Q, and tested for variations in the length of run, queue capacities, blocking, and changes in the distribution of processing times. A Q-GERT simulation of Caterpillar's DNC line was run to test its sensitivity to the number of pallets, storage stations, and load/unload men and to the number and speed of the transporters. The system also was simulated as if it had a closed-loop power conveyor instead of a transporter to permit comparisons of the two handling systems. The results, reported in [24], indicate that conveyors are generally more productive than transporters for this type of system; economic and reliability factors were not considered.

Data Bases for Simulators - In order to improve user utilization of GCMS, a data base interface was developed with the following objectives:

a) Simplify the task of data input and modification by providing users with clear forms, thus eliminating the need for strict input data formatting, and using default values where applicable;

b) Maintain the specification data in the data base so that both error correction and design changes can easily be performed;

c) Provide a basis for design documentation and for a decision support system.

Since GCMS had already been developed and implemented the data base addition was performed according to the Interfacing Approach [21], as shown in Figure 3*. The basic elements of the data base software include eleven forms; an Input Drive that processes data punched from the forms and stores it in the data base; the data base; an Output Drive that extracts data from the data base and structures it in the strict format and sequence required by GCMS.

To specify a CMS facility ten forms are filled by a designer with data about part types, work stations, carts, track, and initialization data. One other general form can be applied for deletions or changes in data already stored in the data base. Data punched from the forms is processed automatically by the Input Software Drive, and stored in the data base (according to the logical structure shown in Figure 4*). During this stage analysis and verification checks of the input data are performed, and messages are printed when errors are encountered. A series of other logical checks is performed each time a user specifies data deletions or changes.

A user can go through the complete process of data input, logical checks, generation of GCMS input data, and the simulation run. Alternatively, a user can just create or modify the data base and produce a printout to check the contents, or use a previously developed data base to generate GCMS input and run the simulation. The data base interface programs were programmed in Fortran using ADBMS subroutines [R2]. They were tested and implemented successfully on several different CMS facilities with significant reduction in user effort. A user manual and complete documentation for the data base software will be available shortly [22].

5. System Productivity and Economic Analysis - Realistic estimates of the attainable output rate for a manufacturing system can be made with the stochastic network model, CAN-Q, developed by Solberg (see above), which takes into account random variations in processing time and congestion delays. By successive application of Solberg's efficient computer program, a capacity expansion pattern can be generated, starting with a minimal system and incrementally increasing bottleneck components. The actual capacity at different levels of equipment investment and manpower requirements can be compared to the theoretical capacity, assuming 100% utilization, and used as a measure of system efficiency. In addition, estimates can be made of production cost at different output rates and the sensitivity of cost to various technical and market factors can be studied. An analysis was made of a typical part produced on a conventional stand-alone line and the results were compared to those for the same part if made on a flexible, computerized manufacturing system (CMS). The breakeven values for CMS production were shown to be sensitive to the production rate, as well as the marginal cost of equipment, labor, and capital; however, the CMS has a consistently higher level of production efficiency than the line. Future work will be directed at improving and generalizing this method of performance analysis.

6. Development of Queueing Models - Work has continued on the development of queueing models and further progress was made in evaluating time utilization in machines that are under adaptive control. A paper on the subject is being written.

7. Interaction Between a CMS and the Plant - Introduction of such "intense" manufacturing unit as a CMS creates various problems in the host plant and even the entire corporation. Both the capability of the CMS and its demands must be considered at all levels - for its proper, economic, utilization. A student spent the summer of 1978 at the Caterpillar complex in Peoria to begin a study of this interaction, which will be continued.

PROGRAM OBJECTIVES FOR THE NEXT 10 MONTHS

1. Consolidate the efforts of modeling existing systems via GCMS, and provide options to the GCMS simulator for the "user-functions" developed to accomplish that modeling.

2. Consolidate the Q-GERTS modeling efforts and compare the characteristics of this manner of modeling with the GCMS and with the CAN-Q approaches. This comparison should be at least with regard to stage of design where the method is likely to be useful and to the ease of access by a relatively naive user.

3. Develop a data-base for the GCMS simulator to provide easier access to the program. This data base should also be applicable to other programs of this type.

4. Develop a complete, practical method for handling the loading problem.

5. Continue to extend the capabilities and convenience of the CAN-Q programs, including separate versions for economic analysis and reliability analysis.

6. Continue with the study of system economics and productivity. Effect of tool management ("flow") policies, tool duplication, magazine size, etc.

* Figures 3 and 4 referred to in this section are on page 9 and 10.

GCMS Information Flow from User to Simulation

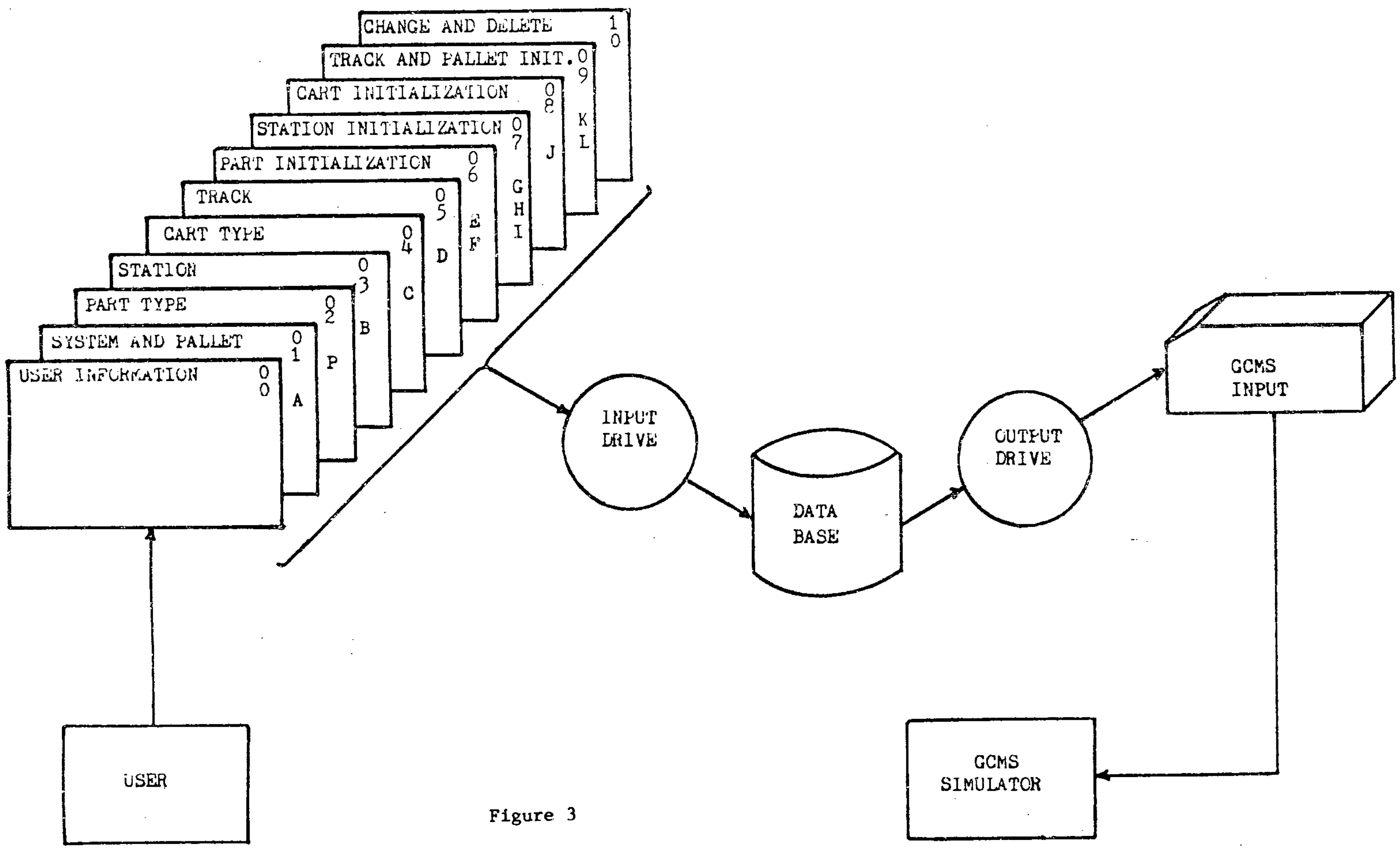

Figure 3

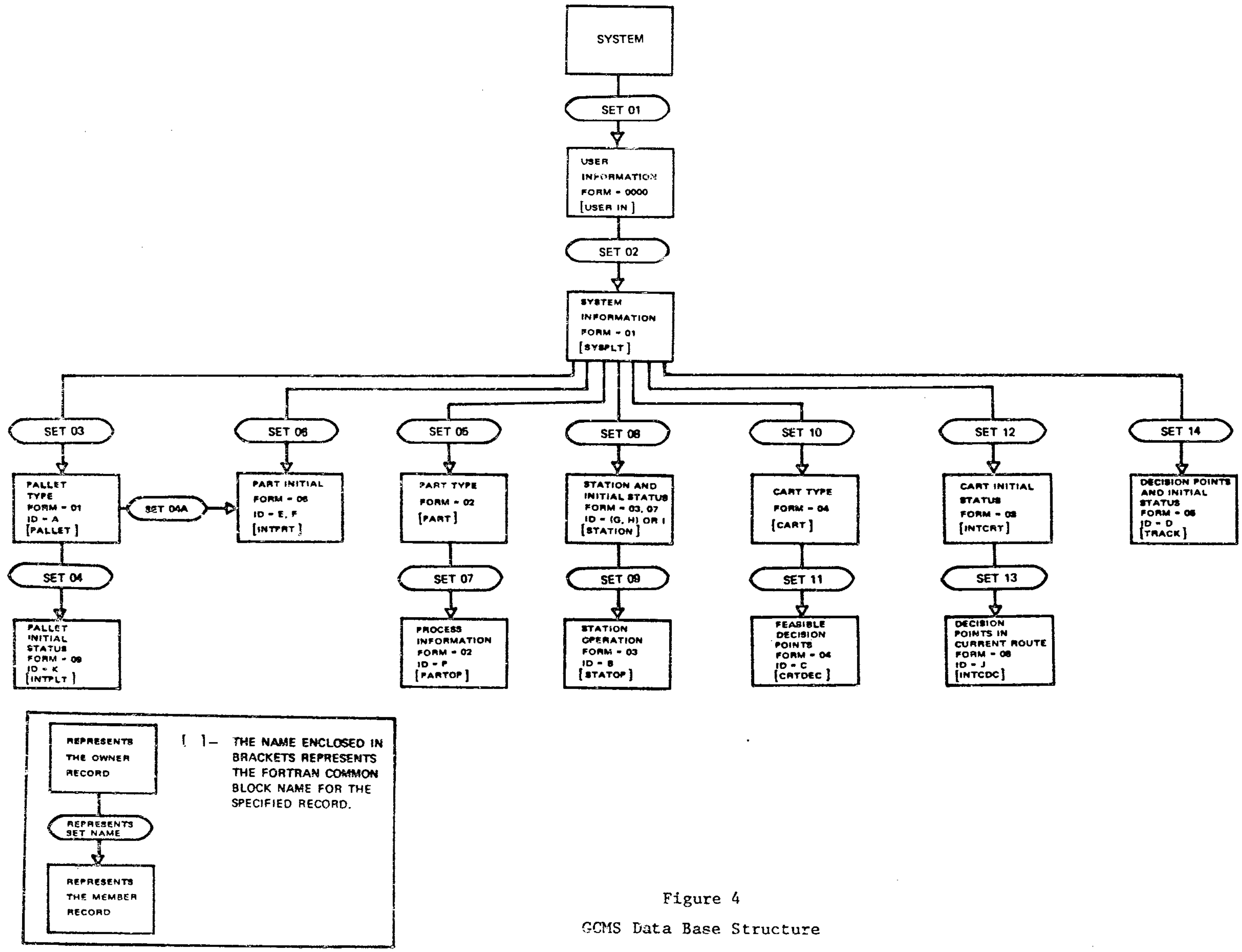

Figure 4

GCMS Data Base Structure

7. Study the materials (primary and auxiliary) flow in a CMS by proper adaptation of the Materials Requirement Planning (MRP) methodology.

8. Continue the study of CMS interaction with the rest of the plant and the corporation as a whole.

9. Develop the principles for composing the control system architecture for the next generation of CMS, accounting for new design features (autonomous tool flow, adaptive control, traveling machines, etc.) and the capabilities of next generation computers (complex software in firmware form, higher speed and capacity).

10. Continue with further refinement of the Unit Machining Operations system (COFORM-APPAS).

11. Continue with analytical work in queueing problems resulting from adaptive control of more than one machine.

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DELIVERABLES

Project Reports No. 4, 5, 6, 7, 8, 9, 10, 11 and 12 are fully documented and can be used by interested parties. In some cases (Reports No. 4, 7, 10) the user must have GASP IV or Q-GERTS capability. All program listings are printed in the respective reports.

COLLABORATORS

CATERPILLAR TRACTOR COMPANY, INGERSOLL-RAND COMPANY, WHITE-SUNDSTRAND MACHINE TOOL

DESIGN AND ANALYSIS OF COMPUTERIZED MANUFACTURING SYSTEMS

FOR SMALL PARTS WITH EMPHASIS ON NON PALLETIZED PARTS OF ROTATION

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PROGRAM OBJECTIVE

Profit maximization and economic growth are generally accepted as fundamental goals for private enterprise These goals are concurrent and depend heavily on increasing the output of available productive resources; ie increasing productivity. In the mass production industries (notably automotive) productivity is high. This has been achieved by 1) transfer lines, 2) automatic assembly machines, 3) excellent fixturing, 4) efficient task management, and most importantly 5) optimal work-flow/inventory control (the assembly line). The efficiency of mass production is realized through economies of scale. The automatic assembly aids (such as welding robots), and fixed assembly lines require large production volume to justify their high cost. The important common factor in all four items above is that each increases the amount of time available for a worker to produce. He does not have to chase after parts, fixtures or the workpiece. All necessary material for his job is automatically delivered to his work station.

Batch production is where goods are made in quantities of 50 - 10000/year. It has been estimated that 75% of all production in this country falls into this category. Generally, due to inventory cost considerations, goods are made in small lots. Individual parts are produced in a large shop along with many other parts of similar configuration and production volume. For each operation, the lot must be moved to the appropriate machine. The machine is then fixtured, checked and the operation run off. The setup is then torn down and the process continued. A number of inefficiencies are evident in batch manufacture: 1) Improper scheduling of various lots into a limited resource shop holds up production. 2) Each machine tool is nonproductive during setup. 3) All setups are repeated for each lot. 4) Tooling and fixturing is, by necessity, simple. A great deal of operator skill and attention is required, causing the resulting operation to be slow.

Part of the inefficiency of batch production has been removed by the numerical control machine. NC machines have reduced setup times and allowed multiple operations to be placed on one machine. In addition, operation times are decreased due to automation of contouring, tool change, head position, etc.

A logical extension of NC is the Computerized Manufacturing System (CMS). A CMS is a group of NC machining centers and inspection stations controlled by a central computer and supplied with parts by a conveyor/robot system (Figure 1). It is capable of simultaneously machining a group of somewhat similar parts that are defined during system set up and programming. The CMS is intended for batch production and is capable of machining different families of parts as production priorities change with only tooling and software modification. (Obviously part class and size cannot change drastically or the machine/line sizes would be wrong).

The CMS has intriguing productivity improvement possibilities. Part scheduling can be optimized and handling is reduced to a bare minimum. "Setup" is eliminated on a non palletized system. If pallets are used, "setup" consists of locating the part to a fixtured pallet once - off line. Thus, many mass production techniques may be adapted to batch production. The potential savings could be immense.

The drawback to a CMS is high initial cost. The gains in productivity must be large enough to cover this cost and still yield a net saving. There are a few CMS systems in existence, so cost data are scarce. Design costs are also high. This fact coupled with a questionable return is causing many potential users to "wait it out".

The goal of our project is to study the CMS from the user's standpoint. We seek to develop computer programs that will: 1) Code and classify part families suitable for CMS, 2) Configure a specific group of machines into a CMS (choose and schedule the appropriate machines), 3) Simulate the behavior of this CMS to determine it's dynamic properties, and 4) Compute the production costs associated with the system including piece cost. The programs are intended for industrial use as tools. They will allow a low cost CMS feasibility study to be made by interested companies. The programs are constructed in a highly interactive fashion and will run on any minicomputer with 48K bytes of core and remote data storage (disk).

RESEARCH RESULTS SINCE THE SEPTEMBER 1977 REPORT

Our project is in its first year so this is the first report. We have carried out research in each of the following areas:
1) Part Processing,
2) System Configuration
3) System Simulation
4) Cost Analysis

Each area encompasses one of our main project goals and each represents a segment of the total computer program. During the year, we have tried to maintain balanced progress in each area with the objective of producing an initial complete interactive system. This first attempt includes, by necessity, errors and approximations that will be corrected later. To reduce the amount of detail further, we have thus far concentrated only on small parts of rotation. These parts are important since they form a large segment of

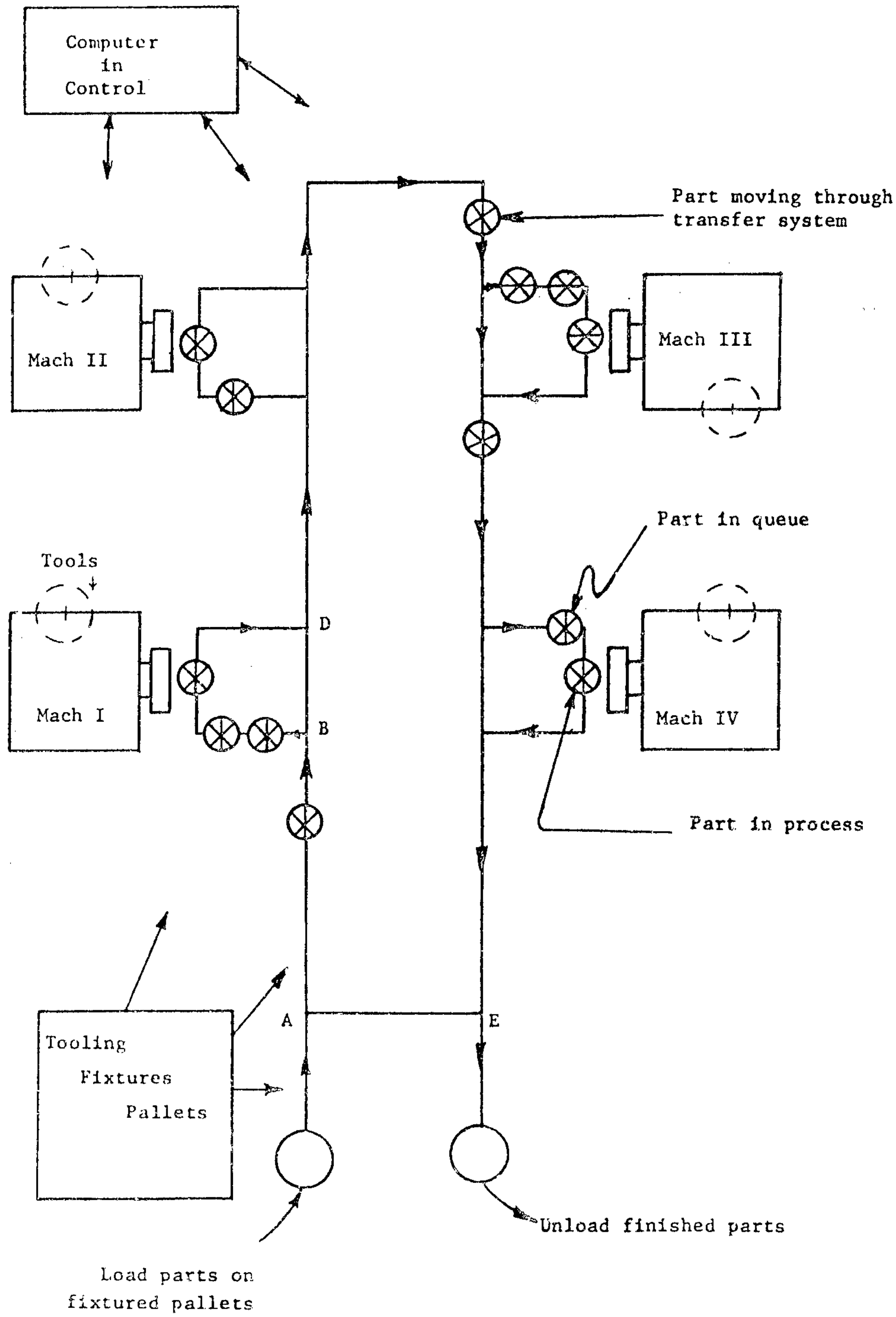

FIGURE 1: TYPICAL CMS LAYOUT

batch manufacture and also allow us to study the effects of short operation times on CMS performance. We have not lost generality in our program by the part size restriction. We have merely made the data more manageable while the program is being developed.

The remainder of this section is devoted to discussion of each of the four research areas. The task our program is to accomplish; transforming any general part mix into a scheduled, costed, and simulated CMS; is complex. For this reason, we shall attempt to summarize with a simple example.

1. Part Processing - Before utilizing our CMS Configuration System the user must decide on which of his current or planned production pieces are candidates for the CMS and what production rates apply. The required input to the part processing routine consists of ordered operation sheets for each desired part consisting of: 1) Operation list
- type of operation (code)

- tool code (material and type)
- recommended feeds and speeds (if any)

2) Workpiece material
3) Surface/tolerance requirements
4) Production volume

The first task of the program is to optimize cutting conditions on all candidate machines for the CMS. The data provided by the user is by no means sufficient to accomplish such a task. The "codes" refer to extensive stored data we have developed, specifically:

- machinability data } relate workpiece material and hardness to tool
- tool data } material and hardness for use in cutting equations
- machine tool data } characteristics of "all" candidate machines for "any" CMS

We have adapted an extended Taylor's equation to optimize cutting conditions for lowest piece cost. In this manner the feeds, speeds, costs and times for each operation on each machine in the universe are obtained.

A flaw in such an optimization procedure is generally due to lack of data. The program, however, has several levels of sophistication. From most to least desirable, the program will:

- optimize using the cutting equations for the specific material-tool combination (if data available)
- optimize using data for proper workpiece and tool materials but different tool type
- use handbook data
- use data gleaned from experience

This portion of the program is interactive so results may be compared and the desired alternative chosen by the user.

At this stage, cutting optimization techniques have been established for drilling, reaming, tapping, milling and turning. These operations comprise the lion's share of all metal cutting processes.

2. System Configuration - The part processing program delivers two major data arrays as output. The optimized costs to perform each of the desired operations on all machines in the stored "universe" are placed in a data matrix, a sample of which is shown in Figure 2. A similar array contains operation times on each machine. The task now is to choose the best group of machines in the universe to machine the given part mix.

The Configuration method is heuristic. It is based on logical concepts and is changed to meet our continually clearer picture of the system. We assume, that allowing for scheduling inefficiencies (traffic jams) and breakdowns, no machine ever exceeds a given target utilization (approximately 70%). We then configure a system assuming perfect workpiece flow and no breakdowns, but limit utilization to no greater than the target. The technique is iterative. We begin by "assigning" each operation to the lowest total cost machine in the universe. Total cost is derived by factoring part transfer time into machining costs. (This technique favors grouping short operations on a given part onto one machine -- an intuitively pleasing result). The resulting assignment sheet for the first iteration will show a very large "system" with low utilization on most machines.

The best system will have all operations grouped on a small number of machines. To accomplish this, the machine with the lowest utilization is deleted from the universe. During the next iteration, all operators are reassigned to the smaller universe. The process continues until the lowest total capital cost system is obtained. During the first few iterations the highly utilized machines are by definition protected from deletion. This places the long or high volume operations on their optimal machines. As iterations progress and assignment alternatives decrease, the lower utilization operations are forced onto these "favored" machines. Though these operations are not produced on their optimal machines, the economic impact of compromising on a low volume operation is favorable to system efficiency. As machines attempt to exceed the target utilization a duplicate is "created", which allows multiple machines in the final system.

Notice that a routing order is a by product of the algorithm. As a part is placed in the system it must travel in order to the assigned machines for each operation. The manner in which the real time assignments are made is saved for the simulation. Another segment of the program assigns backup machines for each operation. The logic is similar to the primary assignment except that provision is made to balance the backup operations over the whole system in event of a machine breakdown.

To continue with the example, refer to Figure 3. Here we have configured a system around the part mix shown in Figure 2. The production volumes are enlarged to compensate for the small number of operations. Notice that it was most efficient to group all of the turning operations on one machine. Notice also that machine 4 was chosen over machine 3 for these operations; its total machining cost (compensated for part transfers) is lowest. This is an unexpected, but correct result. The final item to note is that it was necessary to buy one machine for each of the last three operations. A drill was chosen over more complex turning centers -- a logical result.

3. System Simulation - The simulation has a two-fold purpose. First, it is a tool to prove or disprove the utilizations predicted by the configuration program. Second, it can be used to study the dynamics of the CMS. Most of our work thus far is centered on the second area. Both will be briefly discussed.

OPERATION NUMBER	OPERATION TYPE	TURNING CENTER	TURNING CENTER	TURNING CENTER	LATHE	TURNING CENTER
1	Turning	0.256	0.252	0.149	0.193	0.320
2	Turning	0.256	0.252	0.149	0.193	0.320
3	Turning	0.465	0.464	0.379	0.362	0.564
4	Turning	0.432	0.430	0.342	0.335	0.526
5	Drilling	1.196	0.212	1.187	1000.000	1.414
6	Reaming	0.977	0.988	0.943	1000.000	1.156
7	Tapping	1000.000	1000.000	1000.000	1000.000	1000.000
# TOOLS		14.000	16.000	16.000	8.000	10.000
MACH #		1.000	2.000	3.000	4.000	4.000

FIGURE 2: SAMPLE COST MATRIX FROM PART PROCESSING PROGRAM
PART I

OPERATION NUMBER	OPERATION TYPE	LATHE	TURNING CENTER	TURNING CENTER	DRILL	PART NUMBER
1	Turning	0.232	0.334	0.276	1000.000	8.000
2	Turning	0.232	0.334	0.276	1000.000	8.000
3	Turning	0.414	0.595	0.506	1000.000	8.000
4	Turning	0.385	0.561	0.470	1000.000	8.000
5	Drilling	1000.000	1.524	1.321	0.874	10.000
6	Reaming	1000.000	1.240	1.075	0.718	10.000
7	Tapping	1000.000	1000.000	1000.000	0.389	10.000
# TOOLS		12.000	12.000	12.000	7.000	0.000
MACH #		6.000	7.000	8.000	11.000	0.000

FIGURE 2: SAMPLE COST MATRIX FROM PART PROCESSING PROGRAM
PART II

- Each element is the cost to perform the given operation on the given machine.
- "1000" means operation cannot be performed on the particular machine.

As an integral part of our configuration system, the simulation has a number of tasks:

- Predict overall machine utilizations by including realtime scheduling and breakdowns.
- Predict the sensitivity of the configured system to changes in partmix.
- Act as a feedback loop to modify target utilization and reconfigure a system if necessary.

These tasks have the central goal of helping to improve the configuration algorithm.

The simulation has also been used to study optimal line speeds, pallet quantity and queue size. At this point, the simulation is being jointly developed with Athans et. al. and is reported elsewhere in this volume.

4. Cost Analysis - The cost analysis is a vital service function to the main programs. We have tried to breakdown all costs associated with a CMS. While the costs are not difficult to tabulate, they are difficult to apportion. In order to arrive at a piece cost, the bottom line in a feasibility study, the system related costs must be allocated to each workpiece.

The increasing level of automation in a CMS requires a rethinking of the traditional approach of allocating costs based on Direct Labor Hours. As the principal point where value is added is at the machine tool, and as a large portion of the labor is relatively fixed; it was decided to allocate costs based on the Direct Machine Hours Utilized.

The respective machine tools were considered as production centers while all other supportive components of the system (conveyors, computers, etc.) were considered as service centers. After identifying the fixed and variable costs for the centers, the cost of the service centers were reallocated to the machine tools based on usage of the particular service function. For example a portion of the computer costs was allotted to the conveyor system depending on an estimated computer usage. In turn, the total cost of the conveyor system is allocated to the machines based on number of part input. Finally, the cost per minute to use a machine is obtained by dividing the total costs attributed machine tool by an estimate of its

CMS CONFIGURATION: SUMMARY
FOR DATA FILE PARTMIX02

PARTMIX02 CHARACTERISTICS

PARTS TO BE CONSIDERED

PART NUMBER	PRODUCTION VOLUME
8	80000
10	100000

USER INPUT PARAMETERS

DESIRED MAXIMUM UTILIZATION: .7

DESIRED SYSTEM USAGE:
15 HRS/DAY 5 DAYS/WK 50 WKS/YR

INPUT / OUTPUT TIME: .25 MINS.

FINAL SYSTEM CONFIGURATION

MACHINE NUMBER	UTILIZATION	NUMBER OF TOOLS REQ'D
4 - 1	0.613	4
11 - 1	0.678	1
11 - 2	0.569	2
11 - 3	0.338	3

OPERATION ASSIGNMENT ARRAY

OPERATION	MACHINE	FEED	SPEED	BACKUP
1	4.1	.016	173.	0.0
2	4.1	.016	173.	0.0
3	4.1	.016	173.	0.0
4	4.1	.016	185.	0.0
5	11.1	.009	44.	11.3
6	11.2	.009	58.	11.3
7	11.3	.111	27.	11.2

FIGURE 3: TYPICAL CMS CONFIGURATION

utilized capacity. This may be based on one of the following schemes:

- 100% system utilization
- 70% expected utilization
- actual configured utilization
- actual simulated utilization

The final cost per part is then calculated by summing the respective costs for the operations.

PROGRAM OBJECTIVES FOR 1979

1. Obtain more data for the Part Processing Program. Representative partmixes from industry will be

obtained to exercise the system. Additional Machinability and machine tool data will also be obtained.

2. Integrate the Simulation fully into the system. We shall concentrate heavily on the simulation package in order that it reflect the same level of sophistication as the other programs.
3. Use simulation and industrial partmixes to improve the configuration program. The algorithms must be tested for validity. The flexibility of the configured system to changes in partmix must also be established.
4. Begin dealing with "global optimization". Determine what system parameters give leverage to improving overall performance.

In summary, we have now developed a total package which is almost ready to allow analysis of CMS performance. That analysis will form a large part of next year's work.

DOCUMENTATION

Bilbrey, M.L., "Machining Parameter Optimization for Computer Managed Parts Manufacturing", MIT, Cambridge, Mass., To be published soon.

PRESENTATION

A detailed presentation of our present CMS Configuration Program was held on May 30, 1978. Attending were representatives from: General Motors, General Electric, Cincinnati Milacron, Kingsbury Machine, Draper Labs, Bond Machine, Ingersoll-Rand, Kearney-Trecker, McGraw Edison and Purdue University.

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PROGRESS IN FLEXIBLE AUTOMATION AND MATERIALS HANDLING RESEARCH, 1978*

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August 15, 1978
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I. PROGRAM OBJECTIVE

The goal of the research program is to investigate new methods, models, theories and algorithms for design, operation, real time adaptive control and analysis of flexible manufacturing processes which have the following characteristics:

1. The production process can be represented by an automated network of flow of parts or material to be processed;

2. A variety of alternative production paths can be followed through the network, depending upon the work order to be processed or upon the availability of production units or work stations to process the work order;

3. The work orders to be processed are variable in size, nature, and economic value (batch manufacturing);

4. The production units or work stations can perform automatically a multiplicity of functions under the control of a central computer or a local microprocessor or mini-computer;

5. Interspersed among the production units are automatic inspection or quality measuring stations.

Our research to date indicates that there are fundamental modelling, theoretical, and algorithmic issues that must be addressed before the coordinated hierarchical control of a flexible automated manufacturing system can be successfully obtained, with an increase in the overall productivity and subsequent economic benefits.

Our research deals with issues of system engineering related to

1. System layout topology
2. Strategic operational strategies
3. Real time tactical production control strategies

We believe that there are generic problems that have to be addressed, and our research goal is to provide a unified methodology for addressing and solving such complex issues associated with flexible automated manufacturing networks. To do so, it is necessary to carry out research dealing with

1. Basic system elements, such as machines, buffers, inspection stations, and conveyor mechanisms.

2. Subsystem elements such as flexible work stations, flowshops, and transfer lines.

3. System topology, including networking of machines and subsystem elements and comparison of alternative configurations.

4. Basic optimization studies on both the strategic and tactical level, and subsequent sensitivity analyses.

5. Coordination of the strategic and tactical algorithms.

Each area defines fundamental individual research problems in networks, control, optimization, complexity theory, and algorithms.

II. PROGRAM ACHIEVEMENT

The first year of the program was devoted mainly to preliminary problem formulation and industrial visits. Important research areas were settled on including the effects of finite buffers on reliability, network flow optimization, simulation, and scheduling.

* The research described in this report has been supported by the National Science Foundation under grant APR76-12036.

III. RESEARCH RESULTS (Since 1977 Conf.)

Based upon several visits to industrial plants, discussion with industrial and academic representatives, literature search, and our basic research, we have arrived at the following conclusions.

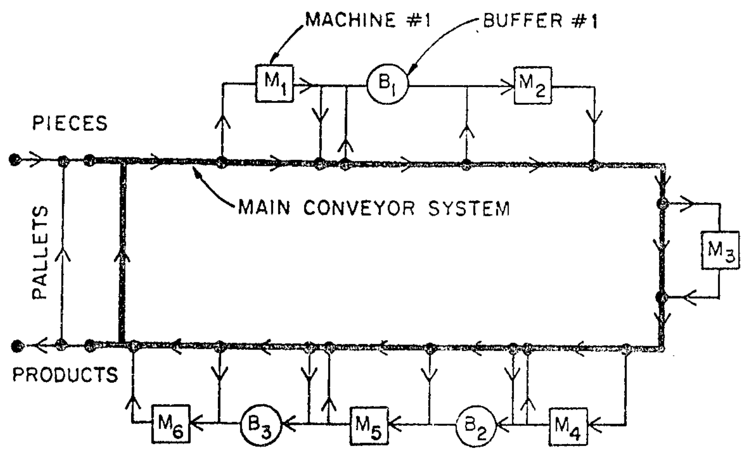

Fig. 1 Example of Flexible Manufacturing System

1. There are many generic problems in batch manufacturing that are common to metal processing, electronic, and process control industries.

2. The major problems are associated with the interface between production planning at a strategic level, and real time tactical decisions on implementing the production schedule in the presence of machine malfunctions and material shortages.

3. Utilization of expensive machines is low, and in-process inventory is high, resulting in decrease in productivity and economic losses.

4. Manufacturers are reluctant to move toward automated flexible manufacturing systems because of the lack of a systematic methodology which can convince them of economic payoffs.

5. Manufacturers are convinced that <u>eventually</u> flexible manufacturing systems will be needed to improve productivity.

6. Our initial research efforts have convinced us that <u>significant</u> improvements in productivity are possible through careful <u>optimization</u> of available resources at several levels. Such optimization will have significant economic benefits.

7. An overall conceptual methodology is <u>not</u> available for formulating, understanding, analyzing, and optimizing flexible automated manufacturing networks. Directed basic and applied research is needed in developing sophisticated methods for

   (a) planning
   (b) scheduling
   (c) real time control

   of such flexible systems, taking into account

   (a) static (steady-state) issues
   (b) dynamic phenomena in production outputs
   (c) stochastic effects arising from machine failures, material shortages, and "recycling" of faulty products

Based upon these broad conclusions, the MIT Electronic Systems Laboratory research team embarked upon a program of basic theoretical research that addressed a subset of the most important problems which we felt were most relevant to batch manufacturing and flexible manufacturing networks. Our philosophy was to identify problems and begin investigations which clearly advanced the state of the art and which, at the same time, were clearly relevant to different aspects of batch manufacturing problems.

One key notion is that of flexibility. Although traditional transfer lines or flow shops with dedicated machines and machine interconnections represent inflexible manufacturing systems, the addition of intermediate buffers introduces options in the scheduling and control of individual machines or line sections, and we have identified needed research in optimizing such systems What are now called <u>flexible</u> manufacturing systems are typified by multi-function machines with networked interconnections, and are capable of handling a mix of different parts. The single-loop system shown in Fig. 1 is an example of a simple flexible manufacturing system in which machines may be scheduled individually or in flow-shop fashion.

The conceptual difference between flexible and inflexible systems is the increase in degrees of freedom in flexible networks; these pay off when stochastic effects (such as machine failures) occur. Needless to say, one needs to carry out a careful analysis of cost vs. complexity for flexible systems. The reason is that more degrees of freedom introduce more points in which real time control (via minicomputers or microprocessors, or even by more trained floor foremen) is necessary. Hence, <u>the real-time computational burden necessary for optimization is an essential ingredient of a flexible automated manufacturing system.</u>

Computational Complexity - We have examined classical flowshops without intermediate buffers as illustrated in Fig. 2. Assuming that each machine must perform an operation on each job in the sequence shown and that the set-up and machine times for each job in each machine are fixed, the problem is to find the optimal job schedule to minimize production time. A new result, important in its own right in mathematical complexity theory, is as follows:

For a large number of jobs n, the optimal scheduling problem is NP-complete if the number of machines, m, is four or greater ($m \geq 4$).

The implication of this result is that even in the absence of machine failures, scheduling a large number of jobs in a bufferless flowshop that contains more than three machines results in a combinatorial problem that cannot be solved in real time by existing computers. On the other hand, we were able to develop fast heuristic algorithms having good accuracy.

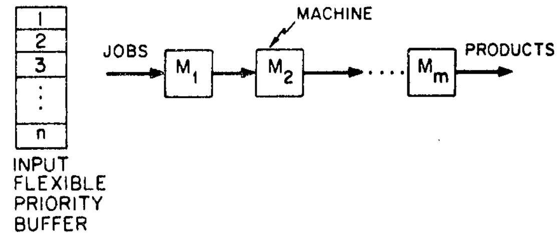

Fig. 2 Buffer-less Flowshop

The Effects of Buffers - If one starts with an inflexible system such as a transfer line or classical flowshop, then one can add a certain degree of flexibility by adding buffers of finite size between the machines. This is illustrated in Figure 3.

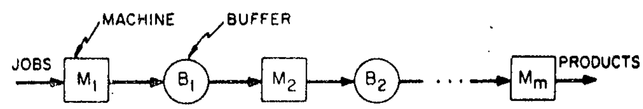

Fig. 3 Transfer Line or Flowshop with Intermediate Buffers

There is a cost that is associated with the introduction of buffers in an otherwise inflexible line. In fact the cost will depend upon

(a) the type of buffer (first-in-first-out or more flexible priority buffers, e.g., carrousels)

(b) the maximum size of the buffer storage

The key question that arises is: what are the payoffs associated with the introduction of buffers?

Our research indicates that the introduction of buffers can have an important payoff in terms of increasing production rates and machine utilization. We carried out, and we propose to continue, two distinct studies on the importance of buffers.

1. What are the effects of buffers in deterministic scheduling?

2. What are the effects of buffers on production rates given machine failure and repair rates?

With respect to deterministic scheduling, we proved that even the two-machine, single-buffer problem is NP-complete, making it certain that for large number of jobs the real time computational requirements to compute the optimal schedule are formidable. Once more this represents a new theoretical contribution to complexity theory. On the other hand we were successful in devising a fast suboptimal scheduling algorithm, with guaranteed performance, which could be used for real time scheduling.

The second area of research that involved buffers deals with the average efficiency and production rates of transfer lines with the general geometry shown in Figure 3. This research effort, deals with the development of both analytical models and computer algorithms that calculate steady state production rates as a function of

(a) the number of machines
(b) the failure probability of each machine
(c) the repair probability of each machine
(d) the size of each buffer

in the cases that

(i) the task execution time on each machine is known and deterministic
(ii) the task execution time on each machine is a random variable.

The latter is particularly important for flexible systems. It can represent a transfer line manufacturing a mix of parts. The parts must be similar, since all parts experience the same kinds of operations at the same stations. However, they differ because the operations take different lengths of time for each part.

Considerable progress in this important area has been made, but much more research needs to be done. The eventual goal of this research will be to generate an efficient general purpose computer program that can be used to carry out economic tradeoff studies relating transfer line efficiency as a function of individual machine reliability (influenced by maintenance strategies) and size of buffers.

Methodological Implications

Even with the introduction of buffers, transfer lines and flowshops of the type shown in Figure 3 are relatively inflexible. In our opinion, the maximum size of such transfer lines or flowshops in a flexible batch manufacturing system should be strongly dictated by the number of precedence constraints (do not execute task k+1 unless task k has been completed). In several industrial visits we found that precedence constraints were artificially established so as to make the life of the floor foreman easier. In our opinion, one should start with physical groupings of precedence constraints to obtain the structure of a flexible system, say of the type shown in Figure 1.

On the other hand the real-time computational requirements of even deterministic scheduling problems (NP-completeness) precludes the overall scheduling of each piece separately. One needs to aggregate the problem so that optimization calculations become manageable.

The approach that we have developed is to utilize the methodology of modern systems engineering to decompose the problem into a hierarchical structure that contains a strategic (economic) level, and a decentralized tactical (stabilizing) level.

Broadly speaking, the task of the strategic (economic) level is to establish the optimal steady-state flows of different product mixes in the different links of the flexible manufacturing network. Means must also be found so that general sensitivity studies could be made to isolate the system "bottlenecks" to carry out system tradeoff studies.

On the other hand, the tactical (stabilizing) level is the system which, based upon real-time measurements, carries out the real time control of individual pieces in terms of scheduling pieces to individual machines, or flowshops, rerouting pieces in case of machine failures, etc. The tactical control strategies are very important, because attention must be paid to modest computational requirements (to be carried out by minicomputers and microprocessors) and to minimum real-time communications and interface requirements.

We have made considerable progress in both the strategic and tactical levels, although much more research has to be done.

Flow Optimization Studies (Strategic)

The objective of the flow optimization studies in a network of flexible machines, interconnected by a loop conveyor system, is to find the optimal steady state routing strategies of different products to different machine stations. In the studies that we conducted we have concentrated in maximizing production rates. The problem has been formulated as a nonlinear multicommodity flow problem, and a variation of the Cantor-Gerla computer algorithm has been used to obtain numerical results for small, but representative, networks.

The input data for the flow optimization program is

(a) the network topology
(b) precedence constraints
(c) time to carry out each operation at each work station
(d) travel time on each link
(e) pallet availability
(f) average loading time
(g) desired production ratios for each distinct product or piece

The optimization program determines the following optimal steady state quantities

(a) the average rate of flow of each product on each network link
(b) the average number of different available pallets, and the probability of pallet availability
(c) the optimal manufacturing strategies for each product
(d) average queue lengths at each work station
(e) average utilization of each machine

The flow optimization approach represents the "heart" of the strategic level controller. Use of the computer subroutines leads to tradeoff studies that can relate changes in production rates to system parameters change (e.g., number of pallets, speed of conveyor system, changes in machining types, etc.).

Networks of Queues Approach (strategic)

Although the flow optimization algorithm can be used for system tradeoff studies, it is not necessarily the best vehicle since it calculates in detail several quantities which, although needed for the strategic level control, are not necessarily relevant for quick and inexpensive tradeoff studies. For this reason,

we have adapted the Purdue CAN-Q program* to analyze flexible loop-type networks. Results to date are very encouraging, since numerical results agree closely with those obtained by the flow optimization algorithm described above, and with these obtained through the discrete event simulation described below.

Several limitations of the present model in regard to loop systems are, however, known. One for example, is its inability to predict the degradation in production rate which occurs when pallet loading is increased beyond a certain point, causing congestion and backups at line-merging points. This could be a serious limitation in more complex networks than those examined to date. The range of applicability of the present model needs to be explored, and research done on locating or developing "computable" models which get around those limitations which are found to occur.

Tactical Control Strategies - In addition to the scheduling research, progress has been made in the tactical stabilizing level. A discrete event simulator that keeps track of each individual piece in the network and carries out real-time control strategies has been developed.

The discrete event simulator has been used, and will be used, as

(a) a test bed for evaluating alternate tactical control strategies
(b) a vehicle for gaining more insight into the real-time dynamic and stochastic phenomena

There can be significant transient and oscillatory phenomena in the actual production rates as compared to the desired steady-state ones. We have been successful in developing control strategies that improve significantly the transient start up phenomena. In addition, we have been able to successfully blend the real-time control strategies with the steady-state optimal strategies derived by the strategic-level flow optimization algorithm, with excellent transient behavior.

IV. PROGRAM OBJECTIVES

In the following we list a set of tasks that we intend to perform over the next three years. We plan to make significant progress along these lines in the next ten months.

TASK 1: TRANSFER LINE STUDIES

Investigate thoroughly the issues relating transfer line efficiency and economic payoffs to machine failure rates, repair rates, size and cost of intermediate buffers. In particular:

1.1) Complete the closed-form solution of the steady state probabilities of three machines and two storages. Extend it to longer lines.

1.2) Complete the numerical technique based on the structure of the transient matrix. Apply to three-machine and longer lines. Study the propagation of error in the recursive matrix multiplications of this approach.

1.3) Study the sensitivity of line efficiency to errors in estimating system parameters. Investigate the variance of the number of pieces produced in a run of a given length. This task will demonstrate how precisely efficiency needs to be calculated, and what degree of approximation is appropriate.

1.4) Study approximate methods for calculating efficiency. This will include the aggregation or disaggregation of storage levels and the replacement of sets of machines and storages by a single, approximately equivalent machine.

1.5) Investigate new models. This will include machines whose operation time is not constant, and it may include failure, or operation times that are neither geometric nor exponential. As far as possible, apply the work of Tasks 1.1 - 1.4 to these new models.

1.6) Consider line layouts that are not linear. Investigate decision problems that arise in such networks. Apply the approaches of Tasks 1.1 - 1.5 to these layouts.

1.7) Consider the line design problem by investigating the optimization of storage sizes, subject to costs of floor space, inventory, machine maintenance and others.

TASK 2: SCHEDULING IN FLOWSHOPS

Investigate the problems of deterministic and stochastic scheduling in flowshops, and analyze in depth the effects of various buffers. Develop and analyze both optimal and suboptimal scheduling algorithms with due attention to real-time computational requirements, and stochastic availability of jobs.

*Solberg, J.J., "Optical Design and Control of Computerized Manufacturing Systems", AIIE Systems Engineering Conference, December 1976.

In particular:

2.1) Complete the on-going studies on deterministic scheduling algorithms and evaluate the cost-effectiveness of different types of buffers upon production rates.

2.2) Analyze in depth the heuristic algorithms, develop upper and lower performance bounds, and carry out stochastic sensitivity analyses.

2.3) Initiate research in stochastic scheduling algorithms for flowshops followed by a testing section that "feeds back" faulty components (Figure 4).

2.4) Initiate research in stochastic scheduling that addresses explicitly the issues of statistical availability of products on the conveyor mechanism, the nature and cost of a sorting buffer, and the nature of a general flowshop (Figure 5).

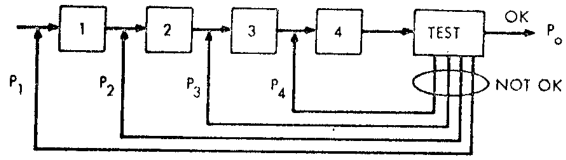

Fig. 4 Flowshop with Probabilistic Recycling of Faulty Components. The P_i Represent Probabilities

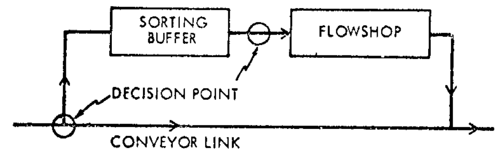

Fig. 5 Subsystem Geometry of a Flowshop in Flexible Manufacturing System

2.5) Fully understand the computational complexity of such stochastic scheduling problems, and develop rules for maximum sizes of flowshops to act as subsystems in the overall flexible automated manufacturing network. Include the effects of storage buffers in the above framework.

TASK 3: DISCRETE SIMULATION

Expand the capabilities of the discrete part simulation so that it can be used as a more effective and flexible test bed. In particular:

3.1) Introduce work station failure and repair capabilities.
3.2) Expand the simulation so that small transfer lines and flowshops with buffers are explicitly modelled.
3.3) Carry out "dimensional analysis" studies so that the overall structure of the discrete simulation is better understood.
3.4) Continue to use the discrete simulation as a test bed for understanding, and evaluating different strategic and tactical control strategies, especially when machines failures and repairs occur in stochastic environment.

TASK 4: NETWORKS OF QUEUES

Evaluate the potential of existing methodologies to predict the machine utilization and production rates for alternate system tradeoff studies. In particular:

4.1) Complete the evaluation of the CAN-Q program as to its accuracy and potential limitations. Compare further CAN-Q predictions with present and future results obtained through both the discrete simulation and the strategic flow optimization algorithm.

4.2) Examine critically the available "networks of queues" literature, adapt it and extend it if necessary, to improve steady state models necessary for the strategic level controller, with special emphasis on proper modelling of queue length distribution at the work stations and the effects of finite queue lengths.

TASK 5: STRATEGIC LEVEL CONTROL

Improve and extend the theoretical and algorithmic aspects of the multicommodity flow optimization algorithm. In particular:

5.1) Refine the optimization algorithm. Establish rules for efficient choice of the penalty Lagrange parameters. Efficiently calculate constrained shortest paths. Incorporate looping paths (due to blocking of products from work stations) in the optimization algorithm.

5.2) Incorporate inspection stations in the model that either remove or recycle faulty components in the network.

5.3) Incorporate additional conveyor loops in the model.

5.4) Determine means by which jobs with different precedence constraints are to be modelled in the multicommodity flow optimization framework. Consider the effects on the overall strategic optimization strategy of some work stations being single flexible machines while others are mini transfer lines and/or flowshops.

5.5) Solve more complex flow optimization problems involving more products, more work stations, and different precedence constraints. Evaluate these optimization strategies using the discrete test-bed simulation (TASK 3).

5.6) Integrate the effects of different tactical control strategies, especially these associated with deterministic and stochastic scheduling (TASK 2), with the strategic optimization level.

TASK 6: DYNAMIC MODELS

Initiate basic research, from first principles, that will result in dynamic state variable models for aggregated production variables. These models should be described by simultaneous differential or difference equations, and they should be able to relate transient changes from desired production rates to simple or sophisticated tactical real-time control strategies. Evaluate these dynamic models using the discrete part test bed simulation. If possible, extend these dynamic models to the stochastic case so that the effects of machine failures and repairs, as well as the probabilistic effects of inspections stations, are adequately modelled.

TASK 7: TACTICAL REAL-TIME ADAPTIVE CONTROL

7.1) Develop techniques for interfacing real-time stochastic scheduling rules (TASK 2) with the overall strategic flow optimization algorithm (TASK 5), with due attention to decentralized control strategies. Test overall system strategies using the discrete simulation test bed (TASK 3).

7.2) Develop new tactical control algorithms for improved transient performance using the new dynamic models (TASK 6) and the methodology of modern control theory. Interface these dynamic aggregate control algorithms with both the flow optimization algorithms (TASK 5) and the individual scheduling algorithms (TASK 2). Evaluate them using the discrete simulation test bed (TASK 3).

V. DOCUMENTATION (Since 1977 Grantees Conference)

1. Athans, M., N.H. Cook, S.B. Gershwin, Y. Horev, P.C. Kanellakis, J. Kimemia, I.C. Schick, J.E. Ward, "Complex Materials Handling and Assembly Systems, Second Interim Progress Report", M.I.T. Electronic Systems Laboratory, Sept. 30, 1977.
2. A multiple volume final report describing the results of our first two years' effort is currently in preparation. The title of the series will be "Complex Materials Handling and Assembly Systems."

Tentative authors and titles of the volumes are:

Volume I - "Executive Summary", by M. Athans, S.B. Gershwin, and J.E. Ward

Volume II - "Multicommodity Network Flow Optimization in Flexible Manufacturing Systems", by J. Kimemia and S.B. Gershwin

Volume III - "Optimization of a Closed Network of Queues", by Giovanni Secco-Suardo

Volume IV - "Discrete Simulation of Flexible Manufacturing Systems", by Y. Horev, N.H. Cook, and J.E. Ward

Volume V - "Algorithms for a Scheduling Application of the Asymmetric Traveling Salesman Problem", by P.C. Kanellakis

Volume VI - "Modelling and Analysis of Unreliable Transfer Lines with Finite Interstage Buffers", by I.C. Schick and S.B. Gershwin

Volume VII - "Analysis of Transfer Lines Consisting of Two Unreliable Machines with Random Processing Times and Finite Storage Buffers", by S.B. Gershwin and O. Berman

Volume VIII - "Numerical Experience with a Closed Network of Queues Model", by J.E. Ward

Volume IX - "Analysis of Transfer Lines Consisting of Three Unreliable Machines and Two Finite Storage Buffers", by S.B. Gershwin and I.C. Schick

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VII. COLLABORATORS

We have not formally collaborated with any companies, although we have made a large number of plant visits. These visits have included:

AMP, Inc.
AMF Harley-Dividson
AVCO Corporation (Lycoming)
Electronic Associates, Inc.
GTE Laboratories, Inc.
Kingsbury Machine Tool Corp.
The Raytheon Co.
Raytheon Marine Products Div.
Raytheon Missile Div.
Raytheon Data Systems
Scott Paper Company
USM, Inc.
Xerox Corp.

A Two-day workshop was held at M.I.T. on May 9 and 10, 1978, at which project results were discussed with 49 attendees from 26 companies and two universities.

"MODELLING AND ANALYSIS OF MATERIAL HANDLING SYSTEMS"

Project Staff*

The University of Michigan
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I. PROGRAM OBJECTIVES - The aim of this project is to develop a computer aided design tool which will assist the designer in identifying material handling system configurations which are worthy of detailed study. Typically, material handling systems are designed from a standard hardware components combined with a few specially designed components and with control logic which is customized for the specific application. Common functions such as merge, select, transport, etc., are realized through a wide variety of combinations of equipment and of physical layouts. Predicting the throughput capacity of a proposed design when operating under the dynamic workloads forecasted by the customer often requires complex and tedious flow analysis. Changes in the customer's perception and understanding of his handling and operating requirements during the purchase negotiation and design phases may indicate the need for a series of this type of analysis. Thus there is a need for a design methodology which uses a mathematical model structure to allow rapid specification of alternative configurations, and quick analysis of the flow characteristics of a system under dynamic loading.

Monte Carlo simulation is a widely and successfully used computer method for modelling and estimating the dynamic throughput characteristics of a material handling system design. It does not however, explicitly indicate the control or layout modifications which would be most cost effective in reducing queues, increasing throughput, or meeting due dates. Consequently, improvements in a system are achieved by drawing on the accumulated experience and intuition of the design engineer. Since simulation is a descriptive and experimental methodology, the designer is often uncertain about the consequences of increasing storage space, removing a conveyor link, providing recirculation, etc., except by rerunning his simulation model for a large number of alternative configurations.

II. PROGRAM ACHIEVEMENT SINCE THE SEPTEMBER, 1977 REPORT

1. Simulation Studies - In the previous report, a simulation system for modelling conveyorized material handling systems, INDECS, was described briefly. Since that report, a user manual for INDECS (project Working Paper 1) has been prepared to describe the features of the simulation system. The INDECS system has been used to simulate the throughput characteristics of conveyor merge designs which were proposed for different applications by two different manufacturers. In both studies, the simulation system provided desired insights about the micro-behavior of the congestion of the flow of unit loads where the space requirements of the load size are critical. One of the studies in which three parallel belt conveyors feed cases at right angles onto either of two takeaway belts is reported in project Working Paper 3. The feeder belts pivot to the level of the takeaway belts which are separated five feet vertically. No gates or sensors are provided to prevent collisions between cases during the merge. Therefore, the cases must be released into the merge at a timing which prevents collisions. Timing constraints and merge alternatives which may be used to achieve a feasible design with desired throughput are defined. The simulation experiments are used to compare the throughput rates for different release strategies, (1) simultaneously release a case on each of the three parallel belts at fixed time intervals, or (2) release an individual case from a feeder when its merge onto the takeaway belt would not collide with an already released case from another feeder. As expected the second strategy is shown to have a higher throughput rate, but requires more elaborate control for implementation.

2. Observations - These simulation studies demonstrated that the INDECS simulation system is able to model subsections of continuous conveyor systems and control in great detail. As a consequence of these studies, a number of modifications seem desirable to simplify the input requirements, to improve the ability to diagnose the user modelling errors, and to improve the format of the output reports. INDECS requires detailed programming skills of the user for modelling the material handling control protocols. Furthermore, INDECS simulates the detailed movement of each and every unit load as it flows through the simulated system. Consequently, the computer time requirements for simulating a large material handling system over long periods of time are large, to the extent of being prohibitive.

   A complete reprogramming would be needed to remove these limitations. We have reason to believe this reprogramming is not likely to contribute toward providing the designer with capability for preliminary analysis of design configurations with a reasonable computing budget.

*A listing is given at end of report.

In our visit to material handling vendors, we observed that the designer analyzes a proposed system at several levels of analysis. For example, the preliminary selection of devices requires a worst case analysis of the steady state flow capacity of the material handling system. Next, the designer may need to analyze the consequences of the different operating schedules of departments using the proposed system. If the conveyor system starts empty each day, does the system achieve required daily throughput if all users report for work simultaneously, or must users start on a staggered schedule? Further analyses may be needed to examine in detail the accumulation and flow capacities required because of random occurrences during the peak periods, and the bottleneck locations. Finally, micro-simulation may be used to verify the ability of the proposed design to satisfy the specified spatial and flow constraints.

Our discussions with vendors disclosed that the flow analysis preceding the micro-simulation step is often performed manually by the designer. The task is tedious, time-consuming, and largely intuitive. As a consequence only a limited set of alternatives are examined. Therefore, we directed our research efforts to developing an analytic tool which is structurally consistent across the several design phases and levels of detail.

3. Dynamic Network Modelling - The analytic tool, called DYNAFLO, we are developing makes use of network flow modelling and optimizing. Compared to common industry practice, it

- provides an analysis of dynamic flows over time in addition to the typical static flow analysis,
- is in the spirit of the paper and pencil analysis often practiced except that it is computerized and can encompass a complete material handling system. (Therefore it offers the capability for fast analysis of more alternative designs.)
- avoids the detailed specification, the customized computer programming, and the micro-second perspective typical of simulation modelling,
- allows analysis of the interplay between dynamic schedules and the storage and flow limitations which may inhibit achievement of desired throughput.

A material handling system is represented in a network flow model by a set of nodes connected by directed arcs. An arc represents the potential for passage of items from one point to another. The number of items which flow across an arc per period may be constrained by upper and lower bounds. A cost may be assigned to each item which flows across an arc. In order to model the dynamic behavior of items flowing through a network of nodes and directed arcs, we attach a travel time to each arc. A network flow algorithm is used to find the maximum value of the flow of items over the arcs of the network between specified origin and destination nodes at minimum cost, subject to the capacity constraints.

4. Model Assumptions - Our dynamic network models require three assumptions: the handling system flow can be approximated by discretizing in space, by discretizing time, and by considering all items as homogeneous. These assumptions are compatible with the aggregate levels of analysis useful in concept design. By clever tricks, these assumptions can be circumvented in special cases. Generally, however, our models are restricted to use where these assumptions are acceptable.

Discretization in space implies that we are able to divide the flow path of item movement into a small number of discrete but connected sections. Usually, each physical device will be modelled by one or more sections. Thus point "i" and point "j" may symbolize two distinct points in space which are connected by a two hundred foot long belt conveyor. A second belt conveyor may transport items from point "k" and merge with the first conveyor at "j". Each identifiable point in space therefore is a point where the flow of items originates, terminates, merges, connects, or diverts to another distinct piece of hardware.

We discretize time by assuming that the time for any item to move from one point in space to another is an integer multiple of a basic discrete time unit called the "time-slice." For example, if the time-slice is 10 seconds, it takes either 0, or 10, or 20,... etc., seconds to move from one point to another point in space. The time required to move an item from one point in space to another is a function of the distance between the points, the velocity of the transporting device connecting these points, and the type of the transporting device.

Items moving or being stored in the system are assumed to be all of the same type. Each item is characterized by a critical dimension associated with a particular device and time-slice. For example, during time-slice t all items on an accumulation conveyor i are of length ℓ. Assume q is the number which accumulates on the conveyor in a single line. The total length of items $q\ell$ accumulated on the conveyor can be constrained to not exceed the length of the conveyor section.

One of the benefits of the network model with these assumptions is that the system can be represented by a two dimensional diagram in discrete space and time. Thus, a node at time-slice t and space

row i has flows on arcs in from other points in space and time, and also flows out on arcs to points in space and time. For node (it), we assume that the flows in from preceding space and time nodes must equal the total flows out to succeeding nodes in space and time. The horizontal arcs imply that units remain at the same node from one time-slice to the next. These arcs therefore model carryover of accumulated items from one time-slice to the next. Each of the arcs may have upper and lower bounds on the flow of items from one space-time node to another. For example, an upper bound on a storage arc represents the maximum number of units which can be stored on an accumulation conveyor. An upper bound on a conveyor arc might represent the maximum number of items per time-slice which can flow over that arc, corresponding to the maximum carrying rate of that conveyor section during the specified time-slice. Similarly a lower bound on the input arcs implies that at least that number of units must be accepted by the system during that time-slice. Hence, the bounds on the carryover and flow arcs can be used to model the following examples of performance requirements:

- Each bank must be capable of holding n pallet loads of the product.
- The flow rate shall be at least m tote pans per hour average, with 150% maximum surge capacity.
- The system must be capable of receiving inbound items at the rate of m per hour during the first five hours of an eight hour shift and ship outbound items at the rate of n per hour during the last three hours of the shift.

Material handling devices have different flow and carryover characteristics. Their network space-time diagram representations are specialized according to these flow properties. A crucial postulate of our work is that the space-time operation of a wide variety of industrial transport devices can be modelled by standard micro-models within the node-arc representation of flows from points in space and time to other points in space and time. To be practical, a small number of internal micro-models of transport devices must be available in a library and accessible by generic name only. To use these micro-models, the design engineer must specify only the parameters of the device (e.g., the velocity, length, and name), but need not know the internal node-arc transformations. We illustrate the internal micro-models for a continuous and for an accumulation conveyor. Other examples can be found in project Working Paper #4.

The following notation is used:

τ = the duration of a time-slice in unit time

Δ = the number of time-slices for a unit load to move from input to output of the device

S = the static holding capacity of the device in number of units

F = the maximum flow or production rate of the device in units per time-slice

d = the distance between input and output stations of the device in feet

v = the velocity of a transporter in feet per time-slice

ℓ = the critical length of a unit load in feet

g = the minimum gap between unit loads in feet when flowing on a conveyor.

Continuous conveyors are characterized by items moving everywhere at the same constant velocity and constant headway. Obvious examples are belt, slat, or powered roller conveyors. Thus, only movement and no inventory accumulation is provided. A continuous conveyor with a velocity of v, and a length d between input point i and output point j is modelled by the node-arc structure in Figure 1, where the travel time (in number of time-slices) $\Delta = d/v$, the holding capacity $S = 0$, and the maximum flow rate is $F = v/(\ell+g)$. The symbols in brackets represent the upper and lower bounds on the flow on the arc, per time-slice.

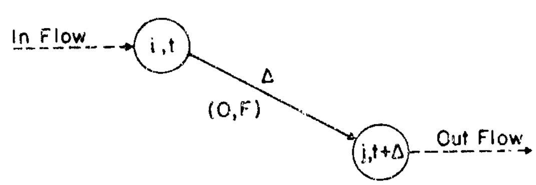

Figure 1. Example of node-arc structure for a continuous conveyor segment between location i and j, with flow time of Δ, and flow rate of F items per time-slice.

Accumulation conveyors are similar to continuous conveyors except that items may queue on the conveyor at the output node, if downstream congestion prevents further flow. If we ignore the acceleration and deceleration, our model corresponds to the flow of unit loads on gravity roller, or wheel conveyors, controlled pressure conveyors, a tow cart system, or in-line power and free system. We assume for this example that the travel time Δ is exactly equal to one time-slice, e.g., $\Delta = d/v = 1$. Then the holding capacity $S = d/\ell$ if we assume items accumulate in a compact queue, and the maximum flow rate in units per time-slice is $F = v/(\ell+g)$. The node arc structure requires two nodes and an inserted arc to model the limited static holding capacity S of the accumulation section and the one time-slice travel delay of a unit from input to ouput on the conveyor link, as shown in Figure 2. The case where the travel time Δ is more than one time-slice is modelled either by a replication of the preceding node-arc scheme for each time-slice, or by a simpler structure which omits the storage constraints.

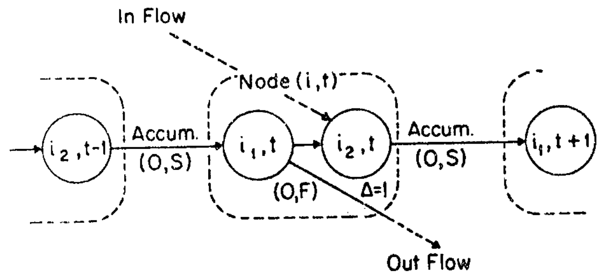

Figure 2. Example of node-arc structure for accumulation conveyor with flow time of 1 time-slice, accumulation space for S units, and flow capacity of F items per time-slice.

To date, we have focused on models which admit to "pure" network formulations; belt, discrete carrier, and accumulation conveyors have this property.

Other devices such as controllers, processors, and elevators do not admit a "pure" network formulation. We have been able to model the operations of these other devices within the more general framework of Linear Programming (LP). Optimization with these other devices is possible using a general LP code but would require substantially increased computer time for solution. An important research topic is the exploitation of the LP structure which these other devices impose so as to avoid the need for a general purpose LP solution algorithm.

5. Software Development - The network modelling concept has been incorporated into both a batch program and an interactive software program for computer aided design studies. The system requires the designer to specify the input, merge, divert, and output nodes of the physical design, the generic type of device (belt, accum conveyor, queue) which links any node pair, the travel time for a unit on each device, the maximum and minimum flow rate in units per time-slice, the maximum holding capacity, in units, of a carryover link, where appropriate, and the cost per unit of an item which flows across a device. The system then generates a static network expanded over a specified number of time-slices, with arc bounds and costs correctly applied for each arc.

A network flow algorithm determines the maximum flow which can be achieved through the network, and produces a report showing the flow of units in each arc for each period of time. Thus, the software package produces a dynamic analysis of the maximum throughput for a given design, revealing the flow fluctuations, congestion, and utilization of all devices.

The interactive system uses a Tektronics 4014 storage tube for input. The input process is considerably simplified, since the designer can "draw" the physical layout of the network to scale on the tube. The program prompts the user to provide correct input data required to develop a valid network model. Both programs are written in PL/1 for the University of Michigan Amdahl 470V/6; thus there is the potential for converting to other types of graphic terminals. The batch version requires about 350K bytes of storage; the interactive system about 400K bytes. Both systems have been used to analyze a variety of small material handling configurations (e.g., 10 stations with 60 time periods, and 15 stations for 60 time periods) provided by the advisory firms. Optimization never required more than 15 seconds of CPU time.

6. Analytic Issues - The development of the time expanded static network concept as a model of the dynamic flows in a material handling design has exposed a rich field of theoretical issues as well as application potential. As a complement to simulation, the network must be able to optimize over possibly 1,000 time periods. Thus models of 10,000 nodes and several times that number of arcs are likely. Presently available algorithms can optimize pure networks of this size. However, the CPU

time may be extensive (of the O (n^2m)) and a million bytes of memory needed to store the network. Therefore our investigations have been directed toward basic modelling questions:

a) Can we develop an efficient dynamic network algorithm which will optimize the flow in a pure network over T periods when the constraints on the arcs change in some periods? An effective algorithm for this problem if the constraints over time are constant, was provided by Ford and Fulkerson[1]. We found that the algorithm for the time varying arc constraint case developed by Halpern[2] is not optimal as claimed. We are currently investigating a subsequent publication on this problem. The applicability of an efficient algorithm to this problem could make dynamic network modelling of material handling systems computationally competitive with simulation modelling.

b) One goal of an analytic approach to modelling is to provide consistent structure and analyses when different time units are used in comparative studies of the same system. For example, the input for an analysis of flows and queues in each hour of a week should be usable and numerically consistent with an analysis of the flows and queues of the same handling system partitioned into sequences of time units aggregated in any arbitrary sets. Thus we may want a model which analyzes system flow on a ten minute by ten minute base for the first three hours of the day, on a minute by minute basis for the next two hours when maximum loading occurs, and on a half hour base for the remainder of the day.

c) In our current version of the system the user can choose a time-expanded model with one time-slice per time period, or with an equal number of multiple time-slices per period and so produce smaller and more easily computed models with some loss of accuracy. Our techniques for aggregating are heuristic. The notion of model aggregation is of importance to the practice of Operations Research in general. Theoretical study of the degree of accuracy or precision lost in material handling system models under various kinds of time and space aggregation is needed.

d) The application of network modelling to a diversity of material handling systems depends upon the availability of micro-models of hardware components such as processors, elevators, stackers, and controllers for more than one commodity type. For efficient computational purposes, we need pure network representations of generic material handling devices. Thus, we are investigating equivalence transformations of networks[3], with initial attention to determining if micro-models which seem to require additional constraints can be transformed into equivalent pure network formulations.

7. Industrial Advisory Committee Activity - Two meetings of an Industrial Advisory Committee consisting of representatives from three material handling system manufacturers were held, in February and in July 1978. We are currently developing arrangements by which an engineer from one of these firms will carry out a "hands-on" test of the DYNAFLO system on a design problem of his choice. The project staff also made two or more visits to each of the advisory firms during this period. The firms were an important source of ideas about design procedures, and have supplied prototype problems and data for our use. In addition to continuing interaction with the advisory firms, project staff have scheduled visits and in some cases maintained regular contact with General Motors Manufacturing Development, General Motors Parts Division, Ford Motor Company Computer Systems Department, Manufacturing Data Systems, Incorporated, Chrysler Corporation Manufacturing Engineering, TRW Michigan, Kenway Corporation, and Herman Miller Research, Incorporated. A brief presentation of the work of the project was made to the National Material Handling Institute meeting in June, 1978.

III. PLAN OVER THE NEXT PERIOD - Our plans over the next period are to continue exploration of the analytic issues identified in the dynamic network modelling. These include investigation of efficient algorithms for the optimization of pure dynamic networks with changes in arc constraints over time, the applications of time and space aggregation on the performance analysis of material handling systems, and the use of equivalence transformations to enlarge the catalog of hardware components which can be modelled by pure networks.

We plan to conduct at least one training workshop to assist one of the advisory firms to test and evaluate the applicability of the dynamic network modelling system on one real material handling situation. The existing software system "DYNAFLO" will be augmented and improved in order to simplify further the input specification, the output data analysis and displays, system diagnostics, and plotting capabilities. These modifications will incorporate comments from users' evaluations. Models of additional devices will be added to the DYNAFLO software catalog.

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[1] Ford, L., D. R. Fulkerson, Flows in Networks, Princeton Press (1962).

[2] Halpern, J.,"p-Period Maximal Dynamic Flows in a Network" Int. J. System Sci., Vol. 7, No. 12, pp. 1403-1415, (1976).

[3] Iri, M., Network Flow, Transportation, and Scheduling, Academic Press, New York pp.120-128, (1969).

IV. DOCUMENTATION

1. Wilson, R. C., "User Manual for INDECS: Integrated Description and Evaluation of Conveyor Systems," Working Paper #1, (September, 1977).

2. Wilson, R. C., "Conveyor Merging Analysis: A Case Study," Working Paper #3, (February, 1978).

3. Maxwell, W. L., and R. C. Wilson, "Analysis of Dynamic Material Handling Systems by Network Flow," Working Paper #4, (March, 1978).

4. Kang, M. K., "Dynamic Network Flow Models of Conveyor Systems," Working Paper #5, (March, 1978).

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VI. DELIVERABLES - PL/1 Program for Dynamic Analysis of Material Handling Networks ("DYNAFLO").

VII. COLLABORATORS

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Ann Arbor Computer Company, Ann Arbor, Michigan
SI Handling, Inc., Easton, Pennsylvania

GEMS: A GENERALIZED MANUFACTURING SIMULATOR

Don T. Phillips, Ph.D.
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PROGRAM OBJECTIVE - The purpose of this research project is to develop a Generalized Manufacturing Simulator (GEMS) which can be used in the analysis of complex discrete part manufacturing systems. A second major objective is to field test this simulation language in selected industrial operating environments. The first objective has been realized and a working GEMS program has been created capable of generalized simulation support capabilities. The result is a FORTRAN based analysis program which can be used to study assembly line or job shop manufacturing environments. The second objective is currently underway, and prototype GEMS models are currently being constructed for a wide range of real-world operating scenarios. These prototype models are being generated through a cooperative effort involving twelve industrial complexes within the state of Texas serving as industrial advisors to the GEMS project. (See Collaborators) Conceptualization of real-world manufacturing environments to the GEMS program is executed via a box/node/arc network representation of the manufacturing system. GEMS is an activity-on-box (node) simulation program composed of standardized simulation input via specialized boxes and arcs. A box (node) /arc structure can be developed to represent complex material flow patterns, probabilistics branching, routing based on attribute values, resource constraints, cost considerations, and complex queueing characteristics. GEMS can be used to study product flow rates, manufacturing capabilities, and queueing phenomena; assess in-process inventories and raw material storage requirements; determine the effects of alternate sequencing and scheduling rules; different routing and material handling schemes; and the impacts of limited resources and increased/decreased production rates. An analysis package has been constructed which normally requires only a representation of the manufacturing system in terms of a network diagram, and transmission of this diagram to the GEMS program structure through FORTRAN NAMELIST data inputs.

The GEMS language embodies the philosophy that the burden of complex systems simulation should be placed upon the simulation language and not the user. To this end, GEMS provides Standard Random Deviate Generators (13 types), a variable time advance clock routine, dynamic storage allocation, automated statistical collection capabilities, and structured modelling methodologies. The synergistic components of GEMS, and those utilized in normal modelling procedures, are the wide variety of box types, logical connectors, and processing capabilities available through GEMS symbology. This type of modelling philosophy is certainly not unique; both GPSS and Q-GERTS employ similar philosophies in their construction and operation. GEMS extends the capabilities of both languages to generalized manufacturing systems through several specialized box types and modelling capabilities.

GEMS is an activity-on-box simulation language. Each box type provides specialized modelling capabilities but in general each box can be characterized by processing costs, resource usage, and probabilistic or constant processing times. A GEMS box is a natural representation of a manufacturing entity or component. A box might represent a transport mechanism, a turret lathe, an assembly line worker or an N/C lathe. Boxes are logically linked by arcs, which represent the functional structure of the system under study. Arcs are precedence relators, routing mechanisms, and logical linkages - arcs consume no time or resources. In addition, special node types can be used to simplify network construction and/or facilitate specialized branching configurations. Development of the GEMS software package provides generalized capabilities for constructing a customized manufacturing model for operations planning control, production system analysis, and engineering evaluations. GEMS is capable of answering the following typical questions asked by manufacturing management: (1.) Which work centers will become bottlenecks to material flow based on the anticipated workload? (2.) How much additional labor/machine capacity will clear the bottlenecks? (3.) What effects will the delay in delivery of raw materials have on the related product shipping schedules? (4.) How should component part production be rescheduled considering several revised/cancelled orders? (5.) How much buffer storage is required at each work station on the production/assembly line? (6.) How much storage space is needed to implement a centralized work-in-process control system? (7.) How much can total throughput time be reduced by routing the jobs to alternative equipment? (8.) What is the estimated cost of material handling associated with a specific product line? (9.) What cost savings may be realized by using each alternative type of material handling system? (10.) What impact will the introduction of a new product line have on the existing factory workload? (11). Which jobs should be given priority for processing at a common work center? (12.) When should preventive maintenance be scheduled to minimize disruption to the existing workload? (13.) What effects will the introduction of N/C equipment have on the material flow between related work centers?

The GEMS program is rapidly approaching status of a major simulation language. A 134 page user's manual describing box types, data input, and modelling methodologies has been produced (Phillips, Handwerker, and Piumsomboom), and a second 94 page manual describing applications and management perspectives is also available (Heisterberg and Phillips). Due to the scope of the GEMS language, it is not possible to completely describe language components and GEMS methodology in this report. The best that can be accomplished in this paper is to briefly describe language capabilities and illustrate GEMS models without complete elaboration. The interested user is invited to further pursue GEMS concepts through more detailed report studies or through attendance of a modelling session which will be held at night during the NSF Grantees Conference. (See Documentation, Contracts, and Deliverables)

PROGRAM ACHIEVEMENT - A management summary and technical outline of the GEMS research program was presented at the last GEMS conference. At this time, the GEMS program structure, mode of analysis, symbolism, and organizational structure was just being formed. Virtually no funded project work was accomplished prior to September, 1977. However, the GEMS Project Team is indebted to Dr. Koichi Tonegawa, a former student at the University of Illinois, for initial program development of GEMS under the name of GNS. Tonegawa developed the prototype program structure and pioneered several box types while working with Dr. Gary Hogg and Mr. Mike Handwerker (project team). In addition, the encouragement, vision, and pioneering efforts of Dr. A. Alan B. Pritsker are reflected in GEMS philosophy, style, and graphical representation. Dr. Pritsker's work in stochastic network simulation was inspirational, and the capabilities of Q-GERTS supplied design concepts for several GEMS box types. Indeed, the GEMS program as envisioned at the September 1977 Grantees Conference was never intended to duplicate or supplant Q-GERTS, GPSS, SIMSCRIPT, or GASP; but rather to enhance simulation activities within the manufacturing environment through a carefully designed alternative - GEMS.

RESEARCH RESULTS SINCE SEPTEMBER 1977 - At the current time, GEMS is a complete simulation language capable of simulating generalized piece-part manufacturing systems. GEMS is a user oriented simulation language which serves as an alternative to GPSS, SIMSCRIPT, GASP, and Q-GERTS. Special capabilities incorporated into the GEMS program structure make GEMS especially attractive when modelling manufacturing systems. GEMS is a FORTRAN based simulation language, which normally requires no programming on the part of a user. Based on network representations of problem scenarios, GEMS is capable of simultaneously studying cost, resource, queueing, and flow time characteristics. GEMS networks are box/node/arc representations of physical systems. These are commonly production or manufacturing systems. The entities which are processed or routed through these systems are called transactions. Transactions can possess characteristics called attributes which describe each transaction. For example, a particular transaction might be a piece of steel with certain volume, weight, length, and Brinell hardness that could be associated with the transaction as its attributes. GEMS employs the concepts of generalized activity networks; however, some additional features unique to GEMS broaden the scope of the modelling capabilities and facilitate greater user convenience. A GEMS network is a precedence diagram, and has the following properties: (1) The network consists of directed arcs, boxes (rectangular boxes), and nodes. The arcs represent only the precedence relationships of activities and events. The boxes and the nodes represent activities and events, respectively. A network does not necessarily have any nodes: the nodes are normally used only if necessary to achieve a desired logic. The major difference between a node and a box is that a node does not have any duration as it represents an event or milestone. (A node may be considered as a special case of a box.) A node or box is said to be realized when all precedence relationships necessary to begin the box/node activity have been completed. Everything said about boxes also applies to nodes unless otherwise noted. (2) Network origination and termination are specified through the use of source and sink boxes. A network may have any number of source and sink boxes. All source boxes are released (started) as the simulation begins. The network is realized when a specified number of sink boxes are realized. (3) A logical operation is associated with the input side of a box. The logical operation is characterized by: (a) The number of releases for box (node) realization the first time (referred to as the "number of first releases"), and (b) The number of releases for the realization after the first time (referred to as the "number of post releases"). (c) The transaction holding criterion which is necessary if batch processing is used (if the number of first or post releases is greater than one). Since each transaction carries a set of attributes, when several transactions are combined (batched) the user must specify which attribute set will be associated with the new single (batch) transaction. Any one of the following four criterions may be used to determine which transaction's attributes will be preserved. (a) Last arriving transaction, (b) First arriving transaction, (c) Save the transaction with the smallest value of attribute Y, (d) Save the transaction with the largest value of attribute Y. (4) The output side of each box is also "logical" and is one of the following types: (a) Deterministic Output, (b) Probabilistic Output, (c) Conditional Output--Conditions are associated with each eminating arc. Three types of conditional output (generally branching depending on specified attribute values) may be used: (i) A - attribute values used as probabilities, (ii) TF - take the first branch for which specified conditions are met (TAKE-FIRST), (iii) TA - take all branches on which the conditions are met (TAKE-ALL). (5) Boxes can also have a priority level (zero unless assigned by the user) which may be used to schedule activities when competition for available resources exist. A resource conflict exists when two boxes have been realized (are ready to start) and require the same resource. When priority levels are used, the box with the higher priority level is given the available resources. The lower priority box will receive resources only after the higher priority box(s) are satisfied. Note that if all available resources are utilized, resource blocking can occur. (6) Queue boxes have the capability of storing transactions prior to a service activity. Queue boxes are the most complex and flexible components of a GEMS model, and are characterized by a large set of modelling features. (a) the initial number in the queue, (b) the maximum number of transactions allowed in the queue, (c) the batch size required to begin a service activity. This combination of inputs allows the user to specify processing by batches or single units. This "batch" requirement at a queue box is similar in concept to the "Number of releases" at a standard box type. In addition, a queue box can also be blocked from immediate service due to lack of resources as can any other box. (d) the box the transaction is routed to if it balks (i.e. the queue is full), (e) the queue discipline (8 types), (f) the number of service channels, or the number of parallel processors. (The serving capacity), (g) the transaction holding criterion, (h) the priority level, (i) cost parameters and resource parameters if applicable, (j) the preempt level (if competition for resources), (k) service time density function and the associated time parameters, (l) serial blocking indicator - which specifies that the queue processor can be blocked if its follower's queue is at capacity (an alternative to having the transaction balk at the follower's queue box). Blocking is allowed only at serial single server queue processors. The queue box notation is shown in Figure 2. A dashed line leaving a queue box indicates the box to which a balking transaction is sent. Note that is desired,

all information shown in Figure 2 can be used when drawing GEMS networks. However, this information is for display purposes only.

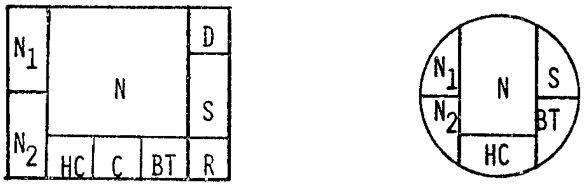
Specialized Boxes: The major function of the distinguishing box is to select a single transaction, from among those waiting at separate preceding parallel queues, to be processed by the distinguishing box. The transaction selection process is controlled by the specification of a selection rule, such as take a transaction from the queue with the largest number of waiting transactions or from the queue with the smallest remaining capacity. A queue may be associated with more than one distinguishing box. Two special cases of the distinguishing box are the assembly box and the match box. The assembly box selects a single item from each member of a designated set of parallel queue boxes (or storage nodes). These items are then treated as a single transaction and the "assembly" activity is performed at the assembly box. The match box is a further refinement of the assembly box in that the transactions selected from the set of preceeding queue boxes must have the same value of a specified attribute, i.e. a "match" must occur before the "assembly" activity is performed at the match box. The selector box has two transaction routing functions: (1) to select one of several following parallel queue boxes (queue selection) or, (2) for "server selection" when non-identical servers exist. The queue selection process is similar to that for the distinguishing box, however, it is conducted on the output side of the selector box, after the completion of its activity. The server selection process is more complex in that the queue of transaction awaiting processing at the server boxes (following the selector box) is held by the selector box. When all the following server boxes are busy the selector box is prohibited from removing any further transactions from its queue until one of the server boxes has completed its processing activity. A box may be specified to be both a distinguishing and a selector box. This distinguishing-selector box can then be used to select from parallel queue boxes, perform an activity on the selected transaction, and then route the transaction to one of several parallel queue boxes. Alternately, this box can select from parallel queues and route the transaction to one of the following non-identical servers. The attribute assignment box is used to assign attributes to each transaction passing through the box. The attribute values may be assigned from any of GEMS' random deviate generators. Additionally, the assigned values may be functions of previous or newly assigned attribute values of the transaction, e.g. attributes may be added or subtracted from the present value. The batch generator box will generate multiple transactions (batches) to be sent to designated follower boxes upon completing its processing activity (e.g. truck unloading). The size of each batch may be generated from any of GEMS' random deviate generators, or may be set equal to any of the incoming transaction's attributes. The order generator serves two functions: (1) initial system loading, and (2) to generate orders (system arrivals) at fixed times, i.e., when orders arrive in a known deterministic fashion. The first use is necessary when attributes control the transaction flow through the model. The storage node is a specialized queue box with zero time duration that is used to store any number of transactions with identical attribute values. The storage node must be used in conjunction with an assembly box (distinguishing box with selection code 1) as only an assembly box can remove transactions from it. The resource control node is generally used to increase the supply of a particular consumable resource, although it may also be used to make a permanent increase in the supply of a regular resource. Lag boxes allow complex precedence relationships to be incorporated into a GEMS network. In conventional networks, the start of an activity depends only on the completion of its predecessors. In addition to the conventional (1) Finish to Start relationships GEMS also allows, (2) Start to Start, (3) Finish to Finish, and (4) proportional relationships to be utilized. A segmentable box, when in progress using a resource of limited availability, can be stopped temporarily at any time. This can occur only when an urgent activity (with a higher priority) requires the resource in use at the segmentable box. The segmentable box will resume progress when the urgent activity is completed and the resource is again available.

There are five box/node types which can be used to alter the structure of a GEMS network model during a system's simulation: (1) swapping nodes, (2) resetting nodes, (3) lag resetting nodes, (4) removal boxes and nodes, (5) removal and set boxes or nodes. The swapping node, when realized, is used to replace some box(s) in the network with another box(s). The resetting node is used to reset the required number of releases to realize a specified box back to its number of first releases. The lag resetting node is used to reset the status of specified lag boxes to their initial state, provided they are in progress or have already been completed when this node is realized. Associated with each removal box (node) is a set of boxes whose activities are to be removed if they are in progress, and likewise any waiting transactions are also removed. Any of the "removed" boxes may be started at a later time if their precedence requirements are met. The removal and set box first performs the same operation as a removal box, and then ensures the "removal" boxes can never be scheduled again.

Costs: When costs are specified for manufacturing activities, GEMS maintains a current record of network costs incurred by various model activities, i.e., the total cost of all activities and associated resources. In addition, the total system (network) may have fixed/variable costs associated with its operation and these costs are included in the total network cost. The network and each individual activity have two associated costs; a setup (fixed) cost and a cost/unit time (variable cost). For boxes with activities which have an associated cost, each time that an activity is started, a fixed and variable cost might be incurred. The setup cost is added to the total fixed costs, and the actual processing time of each activity at a box is multiplied by that box's cost/unit time of operation and this value is also added to the total variable cost. The network setup cost is charged at the beginning of each simulation pass run, and the network cost/unit time is multiplied by the length (in time) of the run. The sum of total fixed costs, and associated variable costs per unit time is the total network cost. The GEMS output report includes a summary of costs associated with resources, group costs, and total box/network costs. A cost/unit time can also be associated with each resource type. This rate is multiplied by how long each individual resource is in use anywhere in the network. Group cost statistics can also be collected

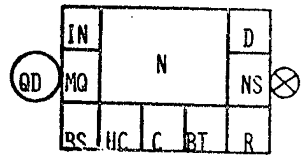
by specifying that a given set of boxes belong to the same group number. GEMS will maintain the total cost incurred by all boxes in each group.

Resources: GEMS allows the specification of three different types of resources: reusable resources, consumable resources, and limited resources. A reusable resource is returned to a resource pool after its use at a particular box (activity) and may be used again at that box or any other box requiring that resource type (e.g., a machine operator or tool). A consumable resource is considered to be consumed at the box (activity) requiring it, and is not returned to the pool (e.g., bolts). Consumable resources may be replenished either through the use of a resource control node, or by specifying a reorder policy and a "supplier" box whose time distribution is the time between arrivals or the lead time. The third resource type is a limited resource and is used when a fixed number (or amount) of that resource is available over the simulation's horizon (e.g., dollars or barrels of oil). Thus, limited resources are consumable resources which <u>cannot be replenished</u> if the supply is exhausted during the simulation. The reason for distinction between consumable resources which <u>are not</u> replenished and limited resources which <u>cannot</u> be replenished is that activities (boxes) requiring more of a limited resource than is available are removed from the waiting list since they can never be scheduled. If this occurs, the GEMS program will alert the user with a non-fatal warning message.



N - Box (node) Number
N_1 - Number of First Releases
N_2 - Number of Post Releases
HC - Transaction Holding Criterion Code
C - Costs are Associated with the Activity
BT - Box (Node) Type Code
R - Resources are Required for this Activity
S - Statistics Collection Code
D - Activity Distribution Code

Figure 1: BOX (NODE) NOTATION



N - Box Number
QD - Queue Discipline Code
IN - Initial Number in the Queue
MQ - Maximum Allowed in Queue
BS - Batch Size (if Greater Than 1)
HC - Transaction Holding Criterion Code
C - Costs are Associated with the Server
BT - Box Type Code
R - Resources are Required by the Server
NS - Number of Servers
D - Service Time Distribution Code
⊗ - Serial Blocking Indicator

Figure 2: QUEUE BOX NOTATION

Data Input and Structure: GEMS utilizes the NAMELIST option for all data input. Each box is described by an appropriate data string specified by direct assignment through a NAMELIST data set. Four NAMELISTS are used by the GEMS program for data input: RUN, RESIN, BOX, and STAT. NAMELIST RUN is required for all simulation runs since it contains overall information for GEMS execution; such as the length of the simulation, the number of resources, the number of boxes, etc. NAMELIST RESIN is required only if resources are used in a simulation run. The characteristics for each box are read in through NAMELIST BOX. It is on these cards that a box's activity duration, resource requirements, etc. are specified. NAMELIST STAT is used to specify the location (box) and type of statistics to be collected for the simulation (and is presently being used to input information about multiple activity boxes). A GEMS user may request various types of statistics to be collected. The requested statistics are collected and their reports are printed out automatically. <u>Time Statistics</u>:--The collection of time statistics may be requested on any non-queue box or node. The box (node) on which statistics collection is requested is referred to as a <u>statistics box</u> (node). The types of time statistics are as follows. (See reports GEMS 4-77 or GEMS 7-78 for details) 1. <u>Delay</u> 2. <u>First</u> 3. <u>All</u> 4. <u>Between</u> 5. <u>Counter</u> 6. <u>Interval</u>. <u>Queue Statistics</u>:--Queue statistics are automatically collected on all the queue boxes in the network unless specified otherwise by a user. The queue statistics collected are (1) number of busy servers, (2) queue length of number of entities in the waiting line, (3) line length (the sum of the number of entities in the waiting line, and entities being processed), (4) waiting time in the queue, (5) percent busy time of the processor, (6) total number of balked entities, (7) total number of entities passed through the processor, and (8) total cost of the processor (if cost is incurred). The statistics on the traversal time of entities going from one point to another in a GEMS network may be collected by specifying a <u>mark node</u> and a <u>flow time statistics node</u>. The mark node stores, as the second attribute of the transaction, the time that the entity passed through the node, and the flow time statistics node collects statistics on the flow time or the traversal time by examining the marked time of the entity. <u>Histograms and Time Shots</u>:-- A user may request the collection of histograms and time shots (discrete time series) on the statistics. The graphical printouts of the statistics are given automatically. The time shot or time profile statistics are collected at fixed time intervals. The time shots may be requested, for example, to analyze the build up of a queue over time. The following discussion is intended to overview the GEMS modelling structure and clarify/augment prior comments.

Selected Examples: In this section, two examples will be presented to illustrate the ease of GEMS modelling. Data input will also be given for Example 1 to show the simplicity of user input.

Example 1: A Single Server Queueing System: The first example is a simple single server queueing process and is shown in Figure 3. Output statistics are automatically provided by GEMS for queue boxes on the

average queue length, busy server percentage, number of balkers, etc.; unless the user specifies that standard queue statistics are not to be collected. In this example, it is also of interest to determine the average time that each transaction (part) spends in the system. Box 1 is the source box for this model. Box 1 is used to generate transaction (part) arrivals to the system with an exponential time between arrivals. Since box 1 has deterministic output, each time box 1 is completed, a part arrives to the system (is sent to node 2) and box 1 is scheduled again, its activity time being the time until the next part's arrival. (exponential) Node 2 is released after each parts arrival. Node 2 is a mark node. Since each transaction enters the system at the mark node, the time it reaches node 2 is recorded in the transaction's second attribute. This mark time, at node 4, is used to calculate how long each part has spent in the system. The only function of node 2 is to mark each transaction. Queue box 3 is the single server (NSERV = 1) processor for the arriving parts. The server is initially empty, and the batch size or number of releases is 1. The maximum queue length is 30. No box for balkers has been specified, so any balking transaction will be destroyed. However, a count of the number of balkers is automatically maintained for each queue box. Node 4 is the sink for the network. Node 4 is also used to collect the statistics on the time each transaction has spent in the system (the flow time statistic). This is accomplished by subtracting the transaction's mark time (the value of its second attribute stored at node 2) from the time TNOW at which the transaction arrives at node 4. TNOW is the variable in GEMS that is always the current simulation clock time. Data Input indicates that node 2 is a mark node and node 4 is used to collect flow time statistics for which a histogram (number 1) of the observations has been requested.

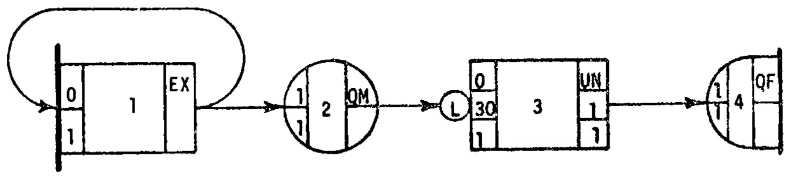


Figure 3 A SINGLE SERVER QUEUEING SYSTEM

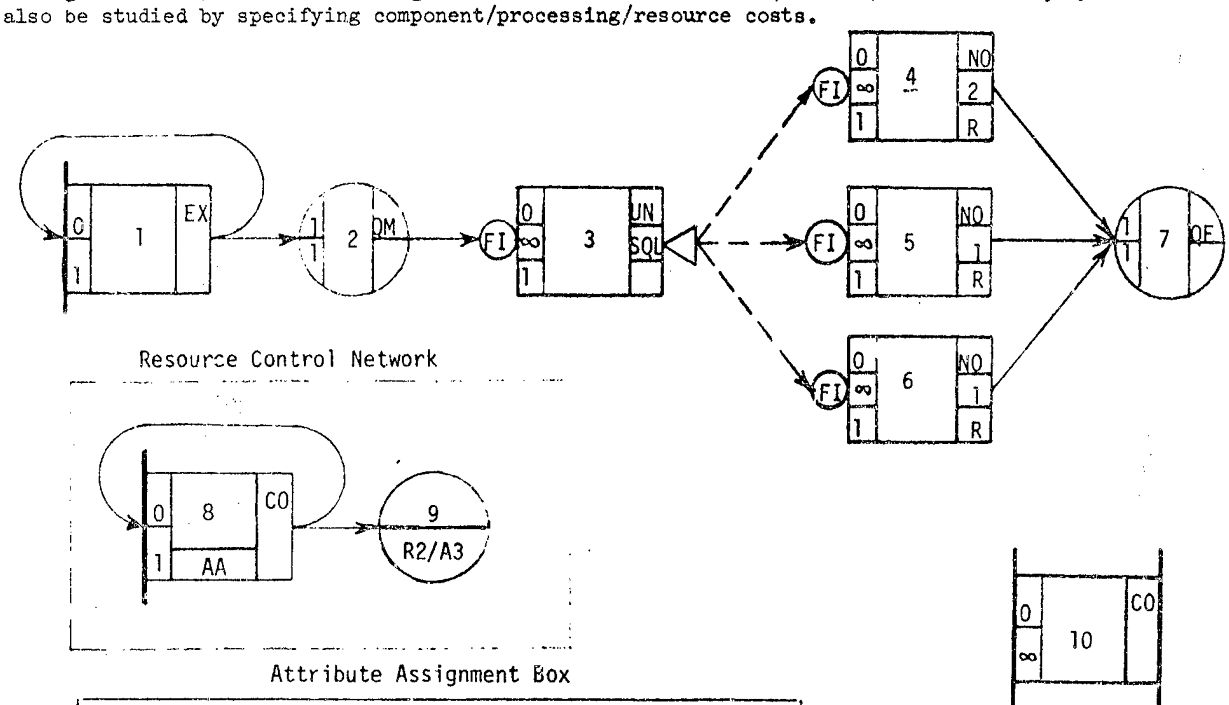
DATA INPUT FOR EXAMPLE 1

```
&RUN IDRUN = 1, MENTRY = 40, NATRIB = 2, NBOX = 4, NOPREM = .TRUE.,
NETRL = 1000, QUE = .TRUE., IPRTY = 3, &END
&BOX ID = 1, NFRL = 0, NPRL = 1, ITYPE = 11, PARAM = 1, 0, 5, IFOLL = 1, 2,
&END
&BOX ID = 2, NPRL = 1, PUR = 0, IFOLL = 3, &END
&BOX ID = 3, QBOX = .TRUE., NPRL = 30, ITYPE = 6, PARAM = .4, 1.4, IFOLL = 4,
&END
&BOX ID = 4, SINK = .TRUE., NPRL = 1, DUR = 0, &END
&STAT IN = -1, 2, 15, 0, 4, 16, 1, HISTL = 0, 0, HISTI = .1, 0, NCELL = 20,
&END
```

Note that the input for each card type is not formatted. Each entry is simply separated by a comma. Data entry must begin in column 2 and can span all 80 columns.

Example 2: Illustration of a Selector Box and Service Activities Utilizing Resources: Example 2 illustrates a situation where a central processor routes work-in-process to four machines. Two machines are new (identical) and two are older (non-identical). The new machines are under DNC control, while the two older machines require manual operation. A part can be made on any machine, and each requires a special attachment (resource). Preference is given to the new machines in routing (processing) items. This example is designed to illustrate the use of multiple resources in a GEMS network. The two new machines are represented by queue box 4, and two older, manually operated machines are represented by queue boxes 5 and 6. Two resources are used in this model. The first resource is a machine operator, required for the activities at boxes 5 and 6, and the second is a specialty item that is attached to each product (job) at every work station. Flow time statistics are collected at Node 7 to allow the evaluation of how fast the jobs are moving through the system. At the start of the simulation, one machine operator and 500 specialty items are available (NOWA), with a maximum of 1000 specialty items allowed (MAXL). The machine operator is classified as a reusable resource and the specialty items as a consumable resource (NRTYPE). Box 1 is the arrival generator and node 2 is a mark node. Selector box 3 performs the function of routing the jobs to the various machines for processing. The routing is done by selecting the queue box with the shortest queue length (NSRULE = 10). This rule would keep box 4 busy most of the time due to its faster service rates and would send jobs to boxes 5 and 6 only if a backlog develops at box 4. A short job preparation activity is performed at box 3. This is reflected by assigning a time duration at selector box 3. Queue box 4 represents the new DNC machines and therefore it has two servers (NSERV = 2). Assuming each machine has its own operator, there is no need to create a resource to indicate this since they would not be used anywhere else in the system and would always be available. Hence, only the need for the specialty item is indicated in the resource requirements. Queue box 5 represents the faster of the two older machines and requires both a machine operator and the specialty item to process a job. When a conflict occurs between boxes 6 and 5, both requiring the machine

operator to process a job, the overall priority scheduling rule IPRTY which is first-in first-out (actually first-come first-served in this case) is used to determine which box gets the resource, and can be started. Queue box 6 represents the slower of the two older machines and also requires both the specialty item and the operator to process a job. Node 7 is used to collect flow time statistics, and box 10 is used to control the length of the simulation. Source box 8 and node 9 are used to model the supply of specialty items. Box 8 is completed every 2400 time units at which time a new order of specialty items arrives. Box 8 is an attribute assignment box, and assigns to the transaction's third attribute the number of specialty items that have arrived in this order. Node 9 is the resource control node that increases the amount of the second resource that is available. The amount of the increase is determined from the arriving transaction's third attribute value that was assigned at box 8. A point of interest in this model is the disposition of a transaction which is routed to box 5 or box 6 when the type 1 resource (laborer) or type 2 resource (specialty item) is not available. In this case, items will be delayed at each box type (in queue) until resources are available. Note that when specified, higher priority boxes will always have "first call" on scarce resources. (This occurs if the user sets IPRTY = 6 and JPRTY = "priority number" for that box). In this example, the rule "first-in first-out" was specified for item processing at boxes 5 and 6 and will govern the user of resources (laborer). If desired, system costs can also be studied by specifying component/processing/resource costs.



Box #	Attribute	Description	Distribution (Mean)
8	3	Order Size	UN (485)

Figure 4 Illustration of a Selector Box and Service Activities Utilizing Resources

PROGRAM OBJECTIVES - A Generalized Manufacturing simulator has been constructed (GEMS) which is capable of simulating a wide variety of complex, flexible manufacturing systems. The ability to simultaneously deal with product/process costs, resources, and queueing characteristics within a programming-free environment greatly enhances the ability to study manufacturing systems. The GEMS language has now been stabilized with regards to modelling components and capabilities. Throughout the remainder of this contract the following tasks will be conducted. (1) GEMS input and output will be revised to make it easier to use and interpret. GEMS output will be expanded to include measures of interest as they arise in field demonstrations. (2) Field demonstrations will be conducted using members of the GEMS advisory staff for prototype modelling efforts. In particular, the following companies will be used. a) Hughes Tool Company-Complete assembly/manufacturing models for the Hughes Tool Joint Line (Houston, Texas) b) Detailed models of the Hughes Tooling processes and the tool supply policies. c) NC and DNC GEMS models for Otis Engineering Company's manufacturing facilities (Sherman, Texas). d) A GEMS model of Versatran Robotic Operations within the manufacturing facilities of Nichols-Kusan, Inc. (Jacksonville, Texas). (3) A major shortcourse in Manufacturing Productivity with nationally recognized speakers will be offered at Texas A&M University in the spring of 1979. A workshop teaching GEMS methodology will be offered. (4) GEMS program refinements and internal changes will be made as the need arises.

DOCUMENTATION, CONTRACTS, AND DELIVERABLES - Since this project was initiated in June of 1977, there have been eight NSF/RANN project reports generated. This report is the second annual Grantees Conference documentation. The following papers are now available for background support material and as supportive evidence of our ongoing research program.

1. An Annotated Bibliography: Systems Analysis Techniques as Applied to Manufacturing Systems; Dr. Don T. Phillips, Dr. R. J. Heisterberg, Mr. John Blackstone, and Mr. Shashikant Sathaye, Research Report GEMS-1-77.
2. Manufacturing Simulation As a CAM Tool, Dr. Rodney J. Heisterberg and Dr. Don T. Phillips, Research Report GEMS-2-77.
3. Definition, Development, and Implementation of a Generalized Manufacturing Simulator; Dr. Don T. Phillips, Dr. Rodney J. Heisterberg, Research Report GEMS-3-77.
4. Development of a Generalized Manufacturing Simulator (GEMS); Dr. Don T. Phillips, Dr. Rodney J. Heisterberg, Dr. Ramon E. Goforth, Dr. Gary T. Hogg, and staff, Research Report GEMS-4-77.
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The research team employed in this project is as follows:

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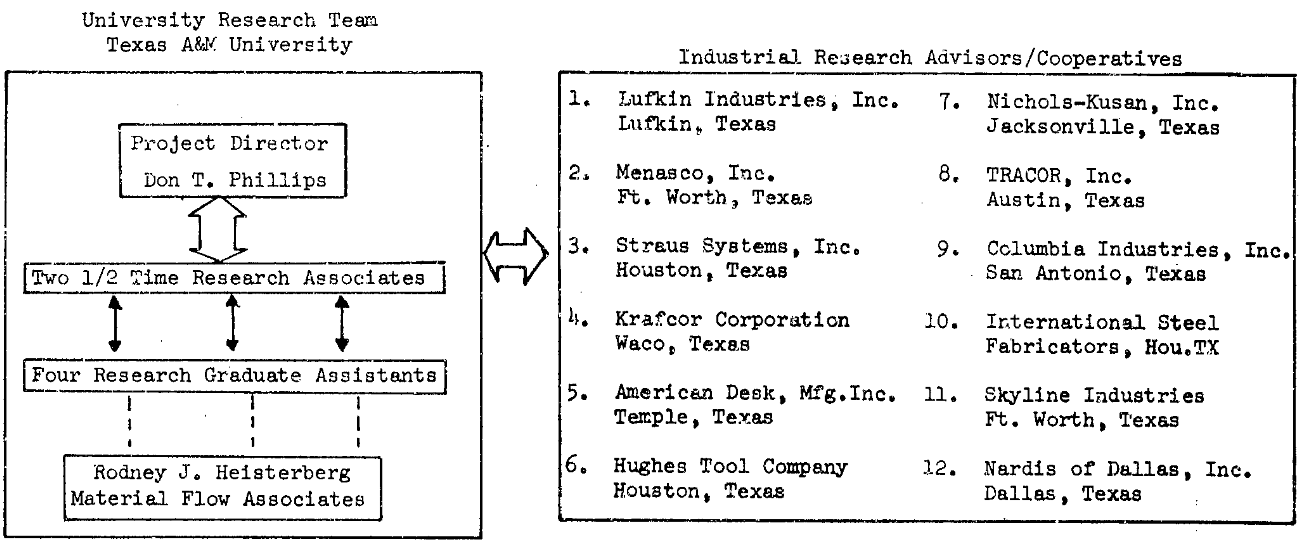
COLLABORATORS - A unique feature of this research is a coordinated, interactive research program involving medium to small sized manufacturing industries. Medium to small size manufacturers will be defined as those which employ 50 to 1000 workers. Specifically, a group of 12 different manufacturing corporations have agreed to actively participate in this research project. Industrial representatives will serve as an advisory board to the research team, and help to specify and structure the final form of the GEMS simulation program. Figure 5 portrays an organization chart which graphically illustrates the interactive structure between Texas A&M University and the industrial consortium. Although each of these manufacturing corporations qualify as a medium to small size manufacturer, the scope of their combined manufacturing activities are tremendous. The range of production planning progresses from 100% job shop operations to highly automated production lines. Technologically, processes involve manual labor, industrial robots, and a battery of contour milling machines which represent a $1.2 million investment. The industrial consortium will continuously interact with the GEMS development, providing technical advice and industrial expertise. Each corporation has pledged their support to this project for the next two years. During the latter 12 months of this project, real-world industrial manufacturing problems will be modelled using the GEMS program within the manufacturing facilities of selected industrial participants. It is believed that this type of industrial cooperation and application will keep the project "honest" and result in a meaningful manufacturing simulator for a wide range of manufacturing situations.



IN-PROCESS OPTICAL GAUGING FOR NUMERICAL MACHINE TOOL

CONTROL AND AUTOMATED PROCESSES

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PROGRAM OBJECTIVE - Over the past 15 years the parts programming/coding, data manipulation, and servo technologies of numerical machine tool control have advanced to a point where the limiting factor is now the technique used for the real-time measurement of the controlled process (and the attendant inferred measurement of the workpiece) in the feedback loop. All transduction methods used today close the loop on the machine slides or the positioning screws leaving machine deflections, tool wear, backlash, screw/nut errors, thermal expansions, etc. outside the control/measurement loop. This research deals with the study of this loop closure by monitoring, by laser optical techniques, the dimension of the actual workpiece as close as possible to the point of contact of the cutting tool so that all machine errors are within the control loop.

All machined surfaces have a significant non-specular property. Our proposed solution to the measurement/control problem is based on this fact. Our measurement scheme involves the use of a small modulated He-Ne laser source focused on the workpiece surface. Due to the non-specular surface property, the scattered light observed from a fixed direction with a position-sensitive photodetector gives the necessary magnitude/phase information to provide a servo tracking signal for mechanical distance measurement to the workpiece surface from a reference station. In this research program a theoretically realizable optical/servo system was physically implemented. Alternate optical geometries, alternate detector systems, and a polarized vs. a non-polarized laser source were investigated, and the optical system performance and response to an extreme range of workpiece surface properties were studied. Finally, the optimized optical gauging system was consolidated, and the response both in optical measurement and closed-loop machine control was studied.

PROGRAM ACHIEVEMENT - Various techniques were considered for making the required distance measurement. It was concluded at an early date that optical techniques offered the greatest promise of making precise workpiece measurements from a remote position. Of several optical techniques for measuring distances, the method selected is a geometric approach, where an incident laser beam is focused on the workpiece, and the image is analyzed with a position-sensitive photodetector. The distance is determined by triangulation. Interferometric techniques are not suitable here because they give relative readings and usually require good reflectors, while in this application direct absolute measurement of non-specular surfaces is required. There appear to be no other special phenomena which can be applied.

The desired performance was achieved in the optical system with measurement precisions of $\pm$ 10 microns ($\pm$ 0.0004") from a distance of 20 centimeters (8"). The measurement principle can be scaled to different sizes and distances, and the precision of the measurement is not directly related to the distance from the optical assembly to the workpiece.

The geometric measurement principle is illustrated in Fig. 1. The incident laser beam and the centerline of a position-sensitive photodetector are focused at the common intersection point, and the photodetector lens forms an image of the scattered laser light from the workpiece on the photodetector. The position-sensitive photodetector determines whether the focal point is in front of, behind, or at the workpiece surface. A servo control loop drives the optical assembly with precision actuators to maintain the focal point at the workpiece surface, and the distance is determined by geometry from the mechanical positions of the optical components. The optical measurement can be achieved by moving individual optical components within the optical gauging head, or by moving the entire optical head with a precision linear carriage. The optical head is considerably simpler and smaller with fixed optical components, and no mechanical problems were encountered in moving the entire optical assembly with a precision servo-controlled slide, so this appears to be the optimum method of implementation.

Extensive experimentation was performed with the optical system on an optical bench. It was quickly found that the reflection from machined workpiece surfaces is very irregular and distorted, with large local variations in reflectivity. The non-specular reflection of the focused laser beam, which was expected to be rather constant, commonly varied over a 10:1 range for small movements of typical workpieces. The overall range of intensity for different machined workpieces was 20,000:1. The large local variations in reflectivity require a very small focused spot diameter at the workpiece, on the order of 15 microns (0.0006"), to prevent excessive shifting of the centroid of the reflected laser light. The non-uniform workpiece surface is the major limitation in the measurement.

Various configurations of the optical system were tested on the optical bench. Due to the random nature of the grain in the workpiece surface, the performance of the optical system cannot be calculated and must be determined empirically. Extensive experimental data was collected and processed to find performance trends with various configurations of the optical system. The optical system was implemented in the arrangement shown in Fig. 2 for testing on an engine lathe.

For evaluating the overall system, the optical system was mounted on a small engine lathe directly opposite the cutting tool, as shown in Fig. 3. The cross slide of this lathe was rebuilt for automatic closed-loop

control, and the entire machine control loop was designed and implemented. All the hardware was constructed and made operational for final evaluation of the complete system.

RESEARCH RESULTS SINCE THE SEPTEMBER 1977 REPORT - All the hardware was completed before the last report, and the overall system was described in the last report. This report presumes knowledge of the previous report regarding the particulars of the experimental machine control system, which are not repeated here.

Since the last report the final system was evaluated and all the research results were compiled. A motion picture of the operation of the final system was completed for demonstration of the results of this program. As of this writing, a detailed report of the entire research project is being prepared, and it will be available for distribution soon after this report is published.

A summary of the characteristics of this optical system is presented here, and the relevant system parameters for application of the gauging principle are discussed.

The desired goal was to demonstrate an optical system which can measure to 13 micron (0.0005") accuracy from a distance of 20 centimeters (8"). The optical head readily meets the desired goal with a precision of better than 10 microns (0.0004") on the optical bench for individual readings or samples of workpiece surfaces. The variance or scatter in the readings is due to random fluctuations of the surface grain of the workpiece. If the workpiece surface is moving tangentially relative to the optical system, the variance of the measurement can be reduced by statistically averaging a number of individual readings. A longer time and a longer segment of the workpiece surface is required for each averaged measurement, but a real improvement in precision is obtained. This method is used in the experimental system, and averaging only 16 individual readings for each measurement results in a typical scatter of 2.5 microns (0.0001"), which rarely exceeds 5 microns (0.0002"). The overall absolute accuracy of the system depends on the stability of the mounting, which adds some error in this experimental system, but which can be greatly improved on a large industrial machine.

The effects of a liquid film on the workpiece were studied by applying a film of oil to each sample surface and comparing the results. The presence of a thick film changed the measured distance randomly either positively or negatively by as much as 50 microns (0.002") in many cases. However, when the oil film was wiped off or blown away with a powerful air jet, the reading was restored to within 2.5 microns (0.0001") of the original reading in almost all cases, even though a stain was still visible on the surface. Thus the presence of coolant or lubricant in machining applications poses no problems. Also the slew rate of the optical system is limited, so that the invasion of momentary chips and scratches has no significant effect.

The optical system determines the position of a surface by triangulation between the incident beam and the centerline of the photodetector. The geometric sensitivity to distance is obviously increased as the angle between the incident beam and the photodetector is increased. This improves resolution up to about 45 degrees, but for larger angles resolution does not continue to improve due to changes in surface reflectivity. The best range is 45 degrees to 60 degrees. In the experimental optical head, a 60 degree angle was chosen because the 32 centimeter (12.5") length of the gas laser requires a long enclosure, and the distance between the beams is used to focus onto the photodetector.

All the experimental data cannot be described here; however, a sample of data pertaining to the experimental optical head is presented.

There is a fundamental difference between measurements made with a micrometer and measurements made with a laser beam or other non-contact gauging method. A machined surface consists of fine ridges and valleys, which form a surface grain. A micrometer measures the peaks of the ridges, and the fit of parts is determined by these peaks. Non-contact methods measure some average of the actual surface. The resolution of surface irregularities with this laser-optical system is determined by the spot diameter at the workpiece and also the orientation of the surface grain, the angle of the incident beam, and the angle of the photodetector.

The direction of the machined surface grain relative to the plane of the incident beam and the optical axis of the photodetector affects the results of the measurement. Data was obtained for the grain oriented either parallel to the plane of the incident and reflected beams, so the laser beam was incident along the grain of the workpiece, or perpendicular to the plane of the incident and reflected beams, so the laser beam was incident across the grain of the workpiece. Due to the surface grain, the reflected light tends to scatter over a much wider angle across the grain, as shown in Fig. 4, which depicts the cross-section of the incident and reflected beams. The reflected laser light is not uniform, but consists of irregular patches of light which move and change shape as the workpiece is moved.

The typical precision of the optical system on smooth machined surfaces is shown in Fig. 5 for different orientations of the workpiece surface. The workpiece surface was perpendicular to the plane of the incident beam and the photodetector and was turned to different angles relative to the incident beam and the photodetector. Similar tests were also made for other angles between the incident beam and the photodetector. From this data the performance of various configurations can be estimated.

It can be seen in Fig. 5 that "specular" reflection gives the best results, and slightly better maximum precision is obtained along the grain, but good precision over a wide range of angles is obtained across the grain. Also, the precision is degraded rapidly when the workpiece s fa:e is turned toward the

incident beam, but good results are obtained when the workpiece surface is turned toward the photodetector. When the machined surface contains coarse grooves, much larger than the focused spot diameter at the surface, as caused by a high feed rate, the actual contour of the surface can be measured along the grain, but this detail is obscured across the grain. When the machined surface contains deep, fine grooves, as occur in turning mild steel without lubricant, incident laser light along the grain penetrates deep into the surface and propagates along the grooves. This gives a measurement considerably below the peaks of the surface. Incident laser light across deep surface grain does not penetrate as far and gives a measurement near the peaks of the surface, which corresponds more closely to the micrometer size of the workpiece. Therefore, the choice of orientation of the optical head relative to the machined grain of the workpiece surface to be measured depends on the surface quality of the workpiece.

In this experimental system, high gauging accuracy was sought at an arbitrary distance of 20 centimeters. The optical system can be scaled for a wide variety of applications, with the same precision of 10 microns. For less critical applications, such as position sensing in robotic devices, the precision can be traded off for a smaller optical head at a given distance from the workpiece surface. These considerations are discussed subsequently.

The ultimate accuracy of this optical gauging system is primarily limited by the surface properties of the workpiece. Due to the random nature of machined and other nonspecular surfaces, the performance of the optical system cannot be calculated and must be determined empirically for the specific types of surfaces which are to be measured. The measurement is affected by actual changes in distance of the surface and by local variations in reflectivity of the surface. These two effects are indistinguishable in the optical measurement process. If the surface is "smooth" and can be moved tangentially relative to the optical head so the distance is constant over a segment of the surface, the variance or scatter in the measurement is random and can be reduced by averaging. Even if the surface is not flat or does not move tangentially, the random scatter can be averaged by curve-fitting techniques. Averaging gives some average measurement of the surface, as do other non-contact gauging techniques.

The variance in the measurement due to local variations in reflectivity of the surface is reduced by reducing the focused spot diameter of the incident light beam. The incident beam illuminates the workpiece surface with a certain intensity profile. If the surface was a uniform diffuse reflector, the scattered light from the surface would preserve the intensity profile of the incident beam at the photodetector and a constant measurement would be obtained. However, actual machined surfaces have highly non-uniform reflectivity, and the intensity profile of the incident beam is greatly altered at the photodetector. This alters the apparent position of the incident light over much of the illuminated area with any type of position-sensitive photodetector which does not employ complex image-processing techniques, and the measurement is affected by this variation in reflected light. The variation in apparent position of the incident light is reduced when the width of the intensity profile of the incident light is reduced. The resolution of fine details in the contour of the surface is also improved both due to finer focusing of the incident light on the surface details and due to reduction of the random variation in the measurement. Therefore, a very small focused spot diameter is necessary for precise measurement. In the experimental optical head, a spot diameter of approximately 12 microns (0.0005") is used to achieve the 10 micron (0.0004") precision.

When the focused spot diameter of the incident beam is increased, there can be some averaging of the reflective properties of the measured surface, but this depends on the spot diameter relative to the spatial frequency distribution of the surface reflectivity, including diffraction effects, under the operating conditions. Without any averaging of the surface properties, the variance in the measurement is proportional to the spot diameter of the incident beam. If the spot diameter is increased enough to cause statistical averaging of the surface reflectivity, the variance in the measurement would become proportional to the square root of the spot diameter. Lack of knowledge of the optical properties of general machined surfaces limits the ability to calculate or extrapolate the performance of the optical system. It is more practical to determine the actual performance of an experimental implementation of the optical system on the desired test surfaces than to determine the optical properties of the test surfaces for the planned configuration of the optical system and calculate the performance.

In addition to variance in the measurement due to non-uniform reflectivity of the surface, the incident light can also scatter and propagate along the surface grain in the workpiece, thereby causing reflected light from areas not illuminated by the incident beam. This is an asymmetrical effect which causes a shift in the measurement. This effect is least significant in regions of high reflection from the incident beam and becomes more significant in regions of low reflection, because the undesirable scattered light is a more major portion of the total reflected light. Due to this effect, it is better to orient the incident beam across the grain in a machined surface whenever possible, especially when the surface has a deep, porous, fine groove structure.

A very small spot diameter of the incident beam is difficult to achieve; therefore, there is a tradeoff between spot diameter and resolution of fine surface detail, variance in the measurement, and averaging of a segment of the surface to increase precision.

Diffraction at the lens aperature is the fundamental limitation in focusing to a very small spot diameter. Aberrations in the optical system may degrade focusing and result in a larger spot diameter, but it is impossible to exceed the diffraction limit in focusing capability. For a coherent incident beam with a suitable cross-sectional intensity distribution, the focused spot diameter is approximately

$$s = \frac{2.5\lambda d}{D}$$

where s = spot diameter, λ = wavelength, d = distance from the lens aperature to the focus, and D = aperature diameter. The focusing properties are shown in Fig. 6. As the diameter of the lens is increased for the same focal length, the diffraction limit for the spot diameter is reduced. However, spherical aberration increases in the lens and focusing becomes increasingly blurred, so more complex lenses are needed to maintain adequate focusing. A coherent incident beam with a flat or spherical wavefront is also essential, so all the optical components in the incident beam must become increasingly perfect as a smaller spot diameter is required.

The gaussian output beam of a single transverse mode gas laser is the best possible light source for focusing. Incoherent light sources are inadequate for any precise gauging applications. Recently experiments were performed in focusing the output of a continuous wave solid state laser diode. Although the output has many asymmetric spatial modes, good focusing was achieved without the usual spatial filtering.

Away from the focal point, the incident beam is a conical spherical wave which can be focused from any arbitrary distance to the same spot diameter, which is determined by the cone angle. Thus the incident beam of the optical system can be scaled to any arbitrary distance and achieve the same spot diameter at the workpiece, which determines the precision of the system. The diameter of the lens can be reduced and/or the distance can be increased if a larger spot diameter is acceptable. The only limitations in scaling the entire optical head are the size of certain optical components, such as the coherent light source and the photodetector, when the optical head is reduced to a very small size, and the mechanical limitations of a very large optical head which must not move from stress or thermal effects.

A position-sensitive photodetector is necessary for any geometric optical system of this type. The capabilities required in the photodetector depend on the application.

An image of the scattered laser light from the workpiece is focused onto the photodetector. The first lens for the photodetector is arbitrarily chosen to have a diameter similar to the focusing lens for the incident beam. Additional lenses may be used to obtain the desired image size on the photodetector. The imaging in the photodetector optics is not as critical as in the incident beam, and optical components of comparable quality are more than adequate because the photodetector is not limited by such nonuniformities as occur at the workpiece surface.

Changes in distance to the workpiece surface cause the image of the scattered light from the workpiece to move across the photodetector. Beyond a certain active range, the image falls completely off the photodetector. There is a tradeoff between a large active range and sufficient resolution in the photodetector to detect very small changes in distance, which is controlled by the magnification of the photodetector lens or lenses relative to the size of the photodetector.

In a system which measures distance over a wide range, a stepping motor drives the optical head to maintain the image of the scattered light from the workpiece centered on the photodetector, and the distance is determined by the position of the precision lead screw which drives the optical head. In this case a simple center null-detector is required to determine the direction of each step of the motor.

In some applications, such as flatness or runout gauges, measurement over a very small range of distance is needed, and the measurement can be made without moving parts in the optical system if a photodetector which can measure absolute position of the image of the scattered light from the workpiece is used.

A modulated laser source is required with any photodetector because the photocurrent generated by scattered light from the workpiece is comparable to the leakage current in the photodetector. A narrowband spectral filter is desirable to eliminate most of the extraneous room light from the photodetector even though modulation is used. Modulation eliminates errors due to DC leakage and offset effects and also unmodulated room light. A modulation frequency of 10 kilohertz was used in the experimental system for rapid response and to avoid beats with machine vibration.

The photodetector now being used is a linear position detector. It employs a large silicon wafer with output terminals at the edges. The photocurrent generated by incident light divides between the terminals as in a resistive current divider due to the uniform sheet resistance of the output junction area of the device. The device is fairly linear over a wide area and very linear over a small area. The output is the sum of all the photocurrents, so over a small, very linear range, the photodetector very accurately measures the true centroid of the incident light. There is a point near the center where the photocurrent divides equally between the outputs. The physical distance from the null position of the photodetector is the difference between the output currents normalized by the sum of the currents. The principle of the photodetector is shown in Fig. 7.

This photodetector can be used for absolute position measurement, but in this application the required normalization of current is difficult due to the very wide range of intensity at the photodetector, which generates proportional photocurrent. If the workpiece moves tangentially, the intensity varies rapidly over a wide range. The output currents can be suitably demodulated and filtered to average the rapid

intensity variations and permit accurate normalization of the output current. Demodulation inherently limits the frequency response to less than half of the modulation frequency, and the required subsequent filtering in this application further restricts the frequency response, but it is still possible to obtain faster response than a mechanically driven optical head. An accuracy of 10% of full range can be achieved easily. Increasing the accuracy to 1% of full range requires sophisticated electronic processing, but it is still simpler than a mechanical servo control system. Since the photodetector responds to distance from the null point, normalization is least critical there, and much better results are obtained near the center of the measurement range. As a null-detector, the photodetector is excellent, because normalization is not needed.

The only photodiode array which could be used here is one with discrete, parallel outputs from each diode. A scanning array, such as a charge-coupled photodiode array, could not be used because the scan rate must be high enough to sample each element at a frequency at least twice the highest significant frequency component generated in the photodetector to recover the modulation. Such a scan rate is impractical. The photocurrent is also too low compared to leakage currents to allow scanning or multiplexing. Therefore, parallel outputs must be individually amplified and processed. To obtain good resolution over a wide range, a large number of photodiode array elements is needed.

A charge-coupled photodiode array could probably be used without modulation if the optical system is arranged in a configuration which gives high scattered light into the photodetector under all conditions. The performance of a charge-coupled array was not considered.

A simple null-detector is much simpler to implement. The linear detector is an excellent null-detector, and it detects the true centroid of the light. A null detector can also be made by splitting the light with a knife-edge roof prism or similar beamsplitter onto two photodetectors and balancing for an equal division of light. Such a photodetector responds to the median of the light instead of the centroid, but similar overall results would be obtained.

When considering an optical system without moving parts, the depth of field of the incident beam must be considered. When a very small spot diameter is required, a wide cone of light is used, and very little defocusing is permissible, so the depth of field is small. For a larger spot diameter, the narrow cone and greater permissible defocusing allow a much greater depth of field, as illustrated in Fig. 6. There are equations for calculating depth of field and spot diameter. The experimental optical head, which was designed for high precision, has a depth of field of only 375 microns (0.015").

The geometric sensitivity of the optical system obviously depends on the angle between the incident beam and the photodetector. The image of the laser light from the workpiece moves farther across the photodetector for the same change in distance as the angle between the incident beam and the photodetector is increased. High geometric sensitivity is needed not due to lack of sensitivity in the photodetector, but because a shift in the apparent position of the incident laser light on the workpiece due to local changes in reflectivity corresponds to a larger change in distance for smaller angles. The performance of the optical system improves as the angle between the incident beam and the photodetector is increased to 45 degrees, but beyond that the results do not improve due to adverse changes in reflectivity as the angle is increased. Therefore, a 45 degree angle is optimum unless there is some other reason for using a larger angle. Typical precision for "specular" reflection for different angles is shown in Fig. 8.

Now, all the parameters pertaining to scaling have been presented. The optical head can be proportionally scaled to achieve the same performance at any distance, as shown in Fig. 9. For large distances, the optical head becomes rather long due to the large distance between the incident beam and the photodetector lens. If maximum precision is not required, the spot diameter of the incident beam can be increased and/or the angle between the incident beam and the photodetector can be reduced, as shown in Fig. 10. Increasing the spot diameter reduces the required diameter of the focusing lens but does not greatly reduce the size of the optical head. If the angle is reduced, the optical head can be made considerably shorter. For non-critical applications, such as 1 millimeter (0.040") accuracy at a distance of 2 meters (79"), the spot diameter can be increased to about 200 microns (0.008") and the angle can be reduced to about 3 degrees for a short optical head with small lenses.

In addition to scaling of the size of the optical head, the sensitivity of the photodetector and the required power of the incident beam must be considered. When the optical head is proportionally scaled, the power levels remain the same. When the configuration of the optical system is changed, the relative power reflected and focused onto the photodetector may change, and photodetector performance must be examined.

The linear position detector is the least sensitive photodetector. The photocurrent generated by the incident light covers the full range of the photodetector, and a small change in position gives a very small change in output current, which is difficult to measure at low incident light levels. In addition, the photodetector has a resistive source impedance, which generates thermal noise current, and performance limited by the thermal noise of the photodetector resistance can be achieved. With a one milliwatt laser and this photodetector, a resolution better than 1% of the active range was achieved on machined surfaces, but the non-specular reflection from highly polished surfaces was insufficient for measurement. Of course, specular reflection from polished surfaces gave excellent resolution.

A photodiode array with individual outputs has much higher position sensitivity because the full photocurrent is available from the illuminated segments, and position is determined by the physical location of

the illuminated segments, with no need to detect very small fractional changes in photocurrent. For fine resolution over a wide range, a large number of array elements is needed, and processing the large number of outputs becomes unreasonable. Photodiode arrays are useful only when sufficient light cannot be obtained for the linear position detector.

When a center null-detector is required, the arrangement using a beamsplitter at the center of the range is much more sensitive than the linear position detector. The linear position detector suffers from the same lack of sensitivity at low light levels, while with the beamsplitter the photocurrent makes a sharp transition between two photodetectors at the center of the range, and there can be a large active range on each side of center, so very fine resolution over a large active range can be achieved at very low light levels where the total photocurrent is hardly detectable. The linear position detector can be made more sensitive as a null-detector by special fabrication which gives a high resistance near the center and low resistance over the rest of the area, so that a sudden change in the division of the photocurrent occurs near the center of the range. There are also quadrant detectors which have split active areas, but there is a relatively large inactive gap of at least 0.05 millimeters (0.002") out of a total length of 10 millimeters (0.400") which makes the devices unsuitable for high resolution.

Recently additional research work was initiated to study the focusing properties of a solid state laser diode. The results were very encouraging, and it appears that a solid state laser can be utilized effectively in the optical gauging system without the spatial filtering which was originally anticipated. A comparison of the original gas laser and the solid state laser source is shown in Fig. 11.

The output of the solid state laser diode emanates in a rectangular beam with about an 80 degree included angle along one axis and a 10 degree included angle along the other axis. This beam exhibits a diffraction pattern showing many finely divided spatial modes along the major axis of the beam and several broad spatial modes along the minor axis of the beam. The output of the laser is coherent, and regardless of this, the specified source size of the laser is 0.25 microns (0.01 mil) by 12 microns (0.5 mil). Simple imaging of the source is diffraction-limited for a normal aperature. Any filtering of the output beam results in an inevitable major loss of power. In this case only about 10% of the 15 milliwatt laser output is collected by the lens aperature, and the image produced is mainly a diffraction pattern of the illuminated lens aperature, with no complex spatial filtering required. The only practical requirement is to effectively absorb the light falling outside the lens aperature to prevent spurious light from the enclosed optical head.

A peculiarity of this particular solid state laser is that there is a null on the major axis of the output beam, and it is necessary to tilt the body of the laser to obtain suitable illumination of the lens aperature. Our current configuration of the optical head with a solid state laser is shown in Fig. 12.

There are many more details in this optical gauging system. The highlights were presented here to acquaint the reader with the properties of this optical system.

PROGRAM OBJECTIVES - All the original objectives were achieved in this research program. Additional research was initiated to study the properties of solid state laser diodes to permit a great reduction in the size of the optical head. Construction of an entirely new and dramatically smaller optical head with a focal distance of about 5 centimeters (2") and utilizing a solid state laser is now under study.

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l. "Lasers give turning a new dimension", Machinery and Production Engineering, May 31, 1978

CONTACTS

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DELIVERABLES - A detailed report with theory and design information is available. There is also a more detailed thesis which describes the particular experimental system developed with this optical gauging principle.

COLLABORATORS - None

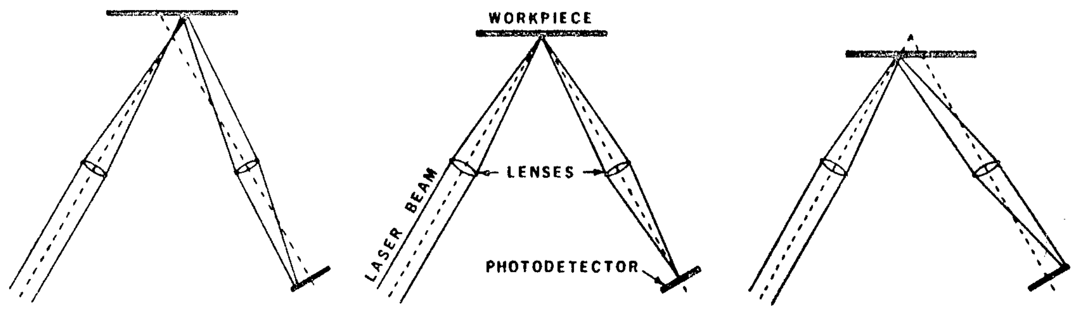


Figure 1. The Geometric Principle of the Optical Distance Gauge.

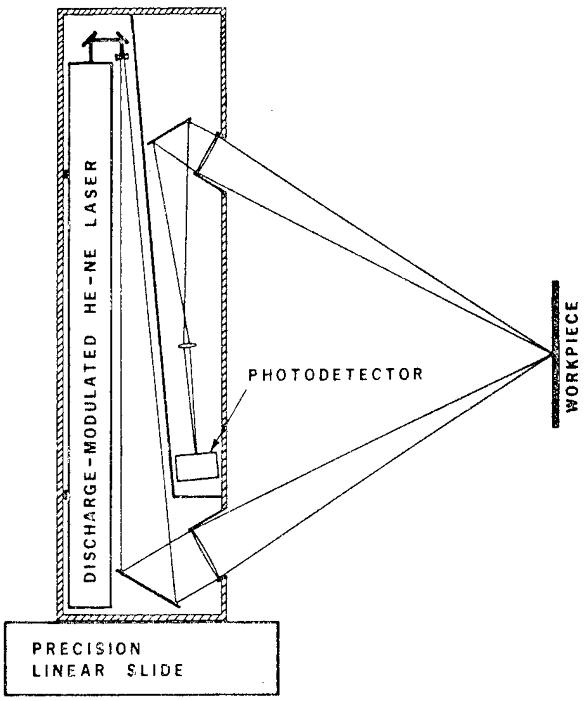


Figure 2. Consolidated Configuration of the Optical Gauging Head.

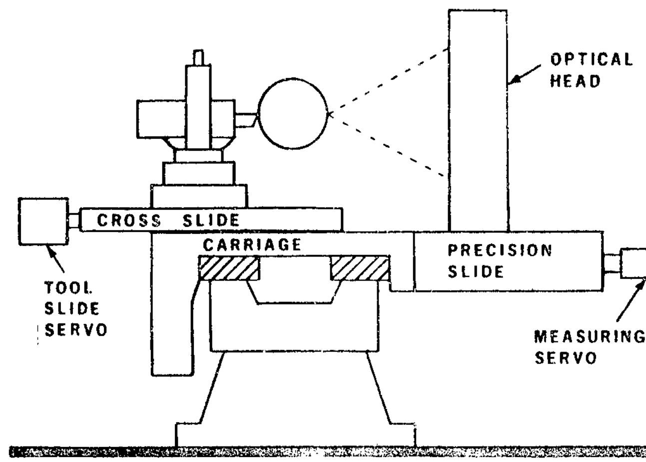


Figure 3. Configuration of the Optical System on an Engine Lathe.

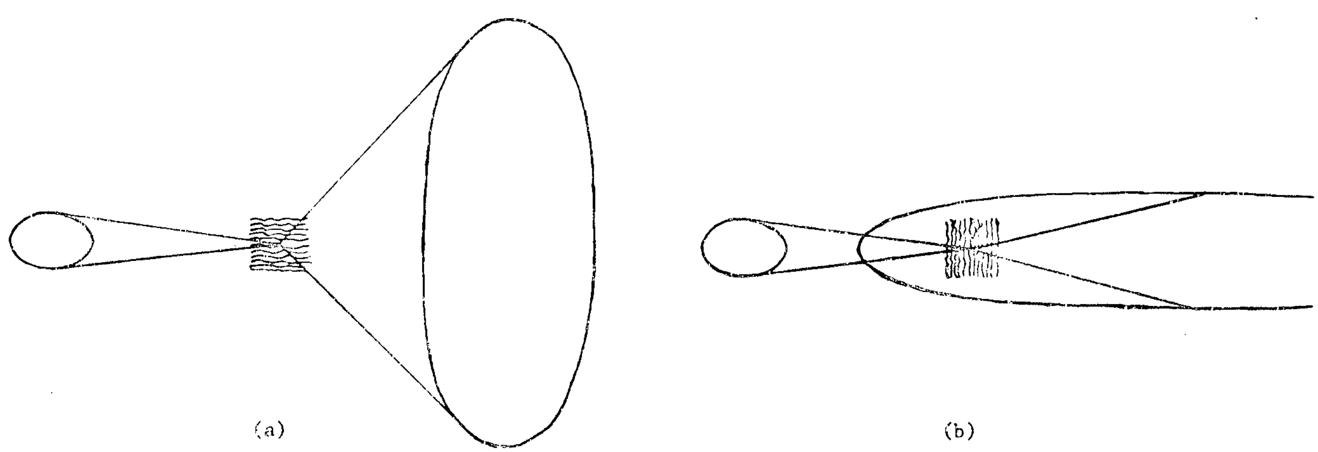


Figure 4. (a) Scattered Light from Beam Incident along the Grain.
(b) Scattered Light from Beam Incident Across the Grain.

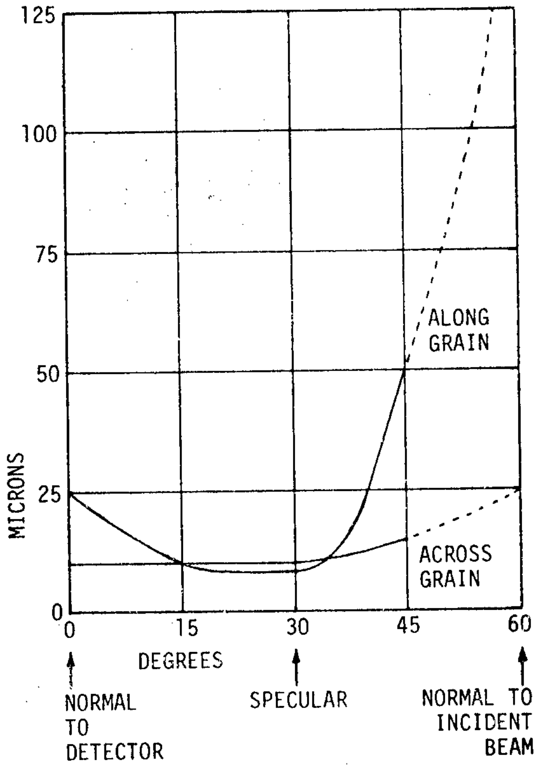


Figure 5. Typical Precision of the Optical System for Various Orientations of the Workpiece Surface.

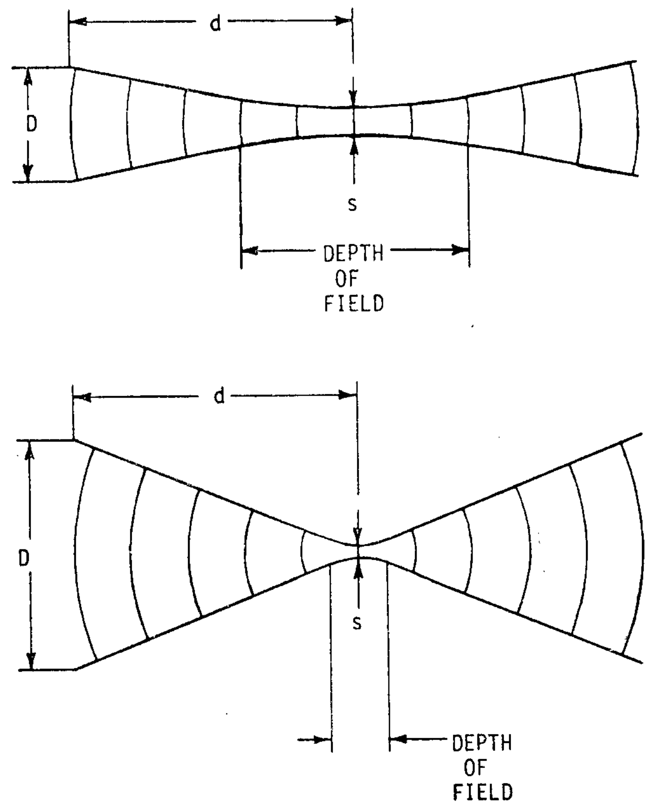
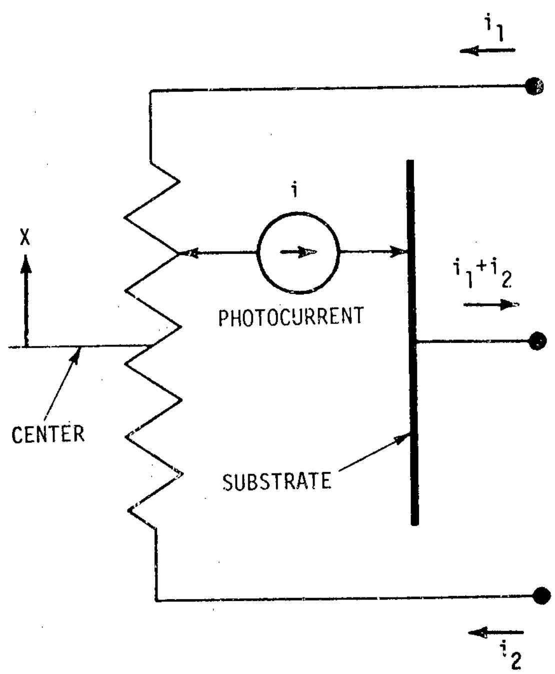


Figure 6. Focusing of Spherical Waves from Different Aperatures.



$$X = \frac{i_1 - i_2}{i_1 + i_2}$$

Figure 7. Principle of the Linear Position Photodetector.

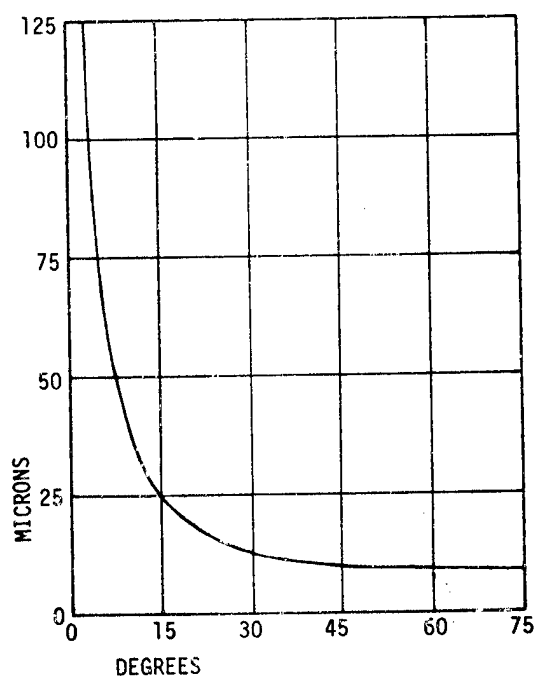


Figure 8. Typical Precision for "Specular" Reflection Versus Angle Between Incident Beam and Photodetector.

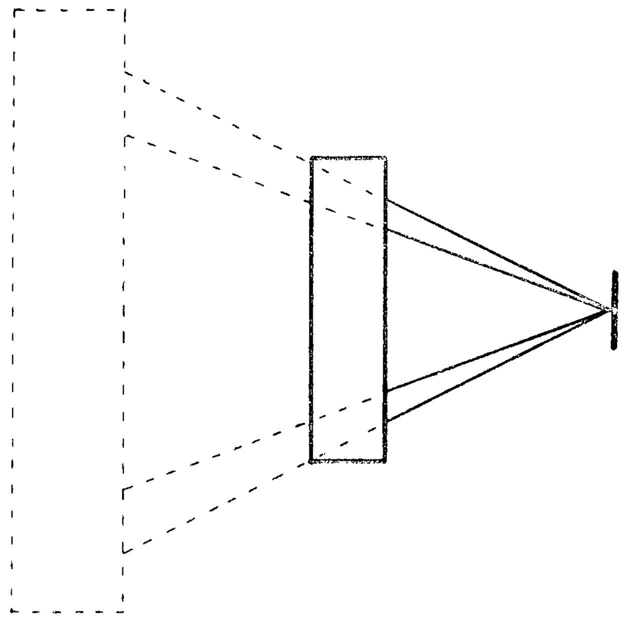


Figure 9. Scaling to Change the Focal Distance for the Same Accuracy.

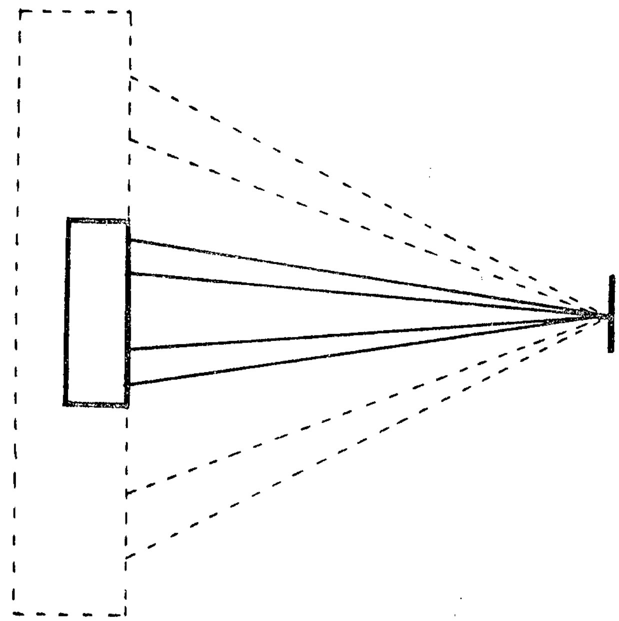


Figure 10. Reducing the Size of the Optical Head for Reduced Accuracy.

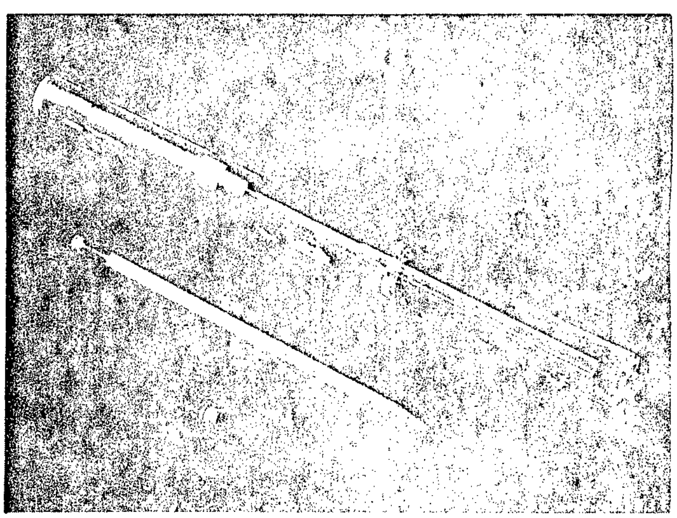


Figure 11. Solid State Laser (Lower Left) Compared to a Modulated Gas Laser and a Standard Pencil.

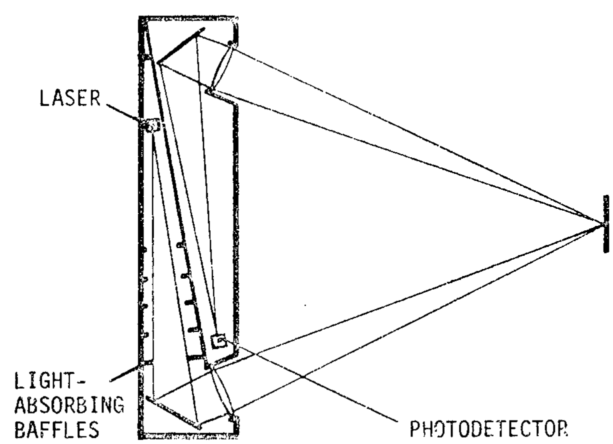


Figure 12. A Possible Configuration of the Optical Head Using a Solid State Laser.

HOLOGRAPHIC LASER MATERIAL PROCESSING

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+School of Electrical Engineering
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PROGRAM OBJECTIVE - Laser material processing systems have been developed to the point where they are now routinely used in production-line environments for such processes as cutting, drilling, and welding. Since optical processes are non-contacting, they offer the significant advantage of not contaminating or exerting any forces on the work surface and there are no problems associated with tool wear as is common with conventional machining systems. Laser systems have been used in precision micromachining operations where they are used to drill holes a few microns in diameter, while by contrast laser machining systems are used in the aircraft industry to cut thick titanium plates.

Laser processing systems normally employ CO_2, Ruby, or Nd-YAG laser operating in either the continuous or pulsed mode. We are concerned primarily with systems that utilize CO_2 lasers operating at the infrared wavelength of 10.6μm. The CO_2 laser has the significant advantage of having high average power (on the order of kilowatts) and high electrical efficiency (on the order of 5 to 15 percent at optimum conditions). A difficulty with CO_2 lasers compared to visible wavelength lasers is that it is difficult to fabricate aberration corrected optical elements for high power beams at these infrared wavelengths.

Our program objective is to develop a holographic projection scheme which can be used to directly deflect the energy of the CO_2 laser into some desired configuration on the work surface. Such a system will potentially simplify the operation of the laser processing system and increase production rates. Conceptually, the simplest procedure would involve producing a hologram of a mask or photographic transparency of the pattern which is to be projected onto the work piece as shown in Figure 1(a). Following the proper exposure, the photographic plate in Figure 1(a) is developed and bleached to produce a phase hologram of the original mask. The real image of the hologram can be projected onto the work surface by re-illuminating the hologram with the conjugate reference beam as shown in Figure 1(b).

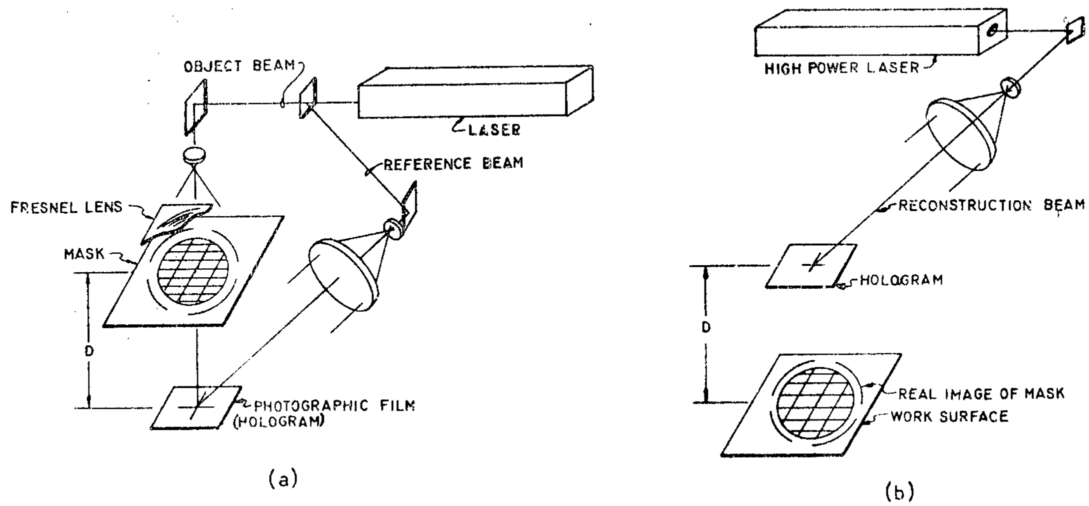


Figure 1. A simple holographic projection system for laser material processing. (a) Recording the hologram. (b) Reconstructing the hologram to project a real image on a work surface.

Unfortunately, there are several fundamental problems that prevent direct application of the above scheme with systems that employ CO_2 lasers. Firstly, photographic films are not sensitive to the CO_2 laser wavelength of 10.6μm. This prevents direct production of holograms using photographic films. Secondly, the extremely high energy flux passing through the holographic plate in the reconstruction process could result in excessive heating of the holographic plate due to the optical absorptivity of the plate or emulsion. Thirdly, the total energy incident on the work material must be sufficient to perform the desired operation, such as welding or cutting.

We believe that we have recently demonstrated significant advances in the solution of these problems. Basically, the infrared hologram is produced using any one of several different possible methods, including recording on thermal detectors and computer generation of holograms. The energy absorption problem is partly solved using a phase reflection hologram. The hologram in this case consists of a mirror-like surface on which the holographic information is recorded by locally modulating the surface height of the mirror.

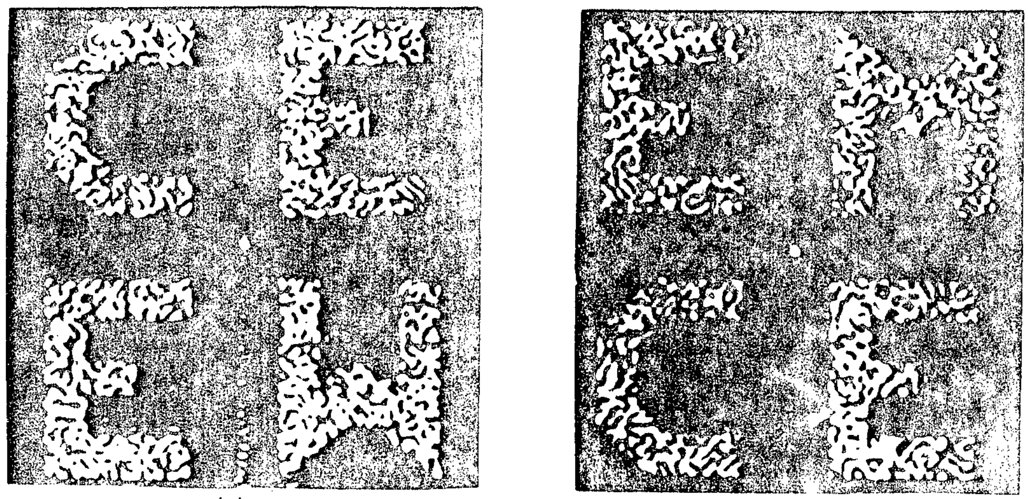
A project related to ours is being conducted at Case Western Reserve University. This project involves a study into the fabrication of rugged reflection holograms. This work is described in the following paper

in this proceeding.

PROGRAM ACHIEVEMENT - Since this project is less than one year old, all program achievements are reported below.

RESEARCH RESULTS SINCE MAY 1, 1978 - There are many possible schemes for recording the computer generated holograms (CGH) needed for this project. Each of the various schemes has its own advantages and disadvantages. In general, the two most important criteria used in selecting the optimum procedure are diffraction efficiency and image quality. A high diffraction efficiency means a high percentage of the laser energy is diffracted by the hologram into a useful image. Good image quality here refers to a measure of the noise content in the image. Unfortunately, obtaining the highest diffraction efficiency and good image quality tend to be incompatible objectives. Briefly, the CGH should encode both amplitude and phase about the optical wavefront to be reconstructed. The CGH that encodes only the phase information (and not amplitude) produces the highest diffraction efficiency. On the other hand, a noise-free image requires that both amplitude and phase information be recorded. We have developed a numerical technique which produces the maximum diffraction efficiency while retaining image quality even if the amplitude information is not recorded.

To demonstrate the capabilities of these techniques we have compared a number of images produced using various schemes. Two of these images are shown in Figure 2. Figure 2(a) shows an image from a hologram in which both amplitude and phase information have been recorded. The image quality is good but the diffraction efficiency of the hologram will be low. Figure 2(b) shows an image in which an iterative numerical technique has been used to suppress the information content in the amplitude. The image quality in this case is also good and the diffraction efficiency is about twice that of Figure 2(a). Comparisons of this type allow the selection of the optimum procedure for producing the necessary holograms.



(a) (b)

Figure 2. Real images from computer generated holograms. The holograms have been reconstructed here with a He-Ne laser. (a) Both amplitude and phase information are recorded. (b) The information content in the amplitude has been minimized to increase the diffraction efficiency.

One disadvantage of using a holographic element to project a pattern is that if the pattern on the workpiece is very complex or large, the resultant energy density in the projected pattern may be too low to perform the necessary material processing operation. We have proposed an alternate method for laser materials processing using computer generated holographic scanners(CGHS). This technique eliminates the complex translation device but maintains a high energy density. An example of a holographic scanner operating in the reflection geometry is shown in Figure 3. A holographic scanner will diffract a laser beam into a single spot that will scan over the desired pattern as the scanner is translated. Since the entire first diffracted order is concentrated into a single focused spot, rather than spread over an extended image, a high energy density is maintained. Only a simple, one-dimensional motion of the scanner is required to generate a complex translation on the workpiece.

As with other holographic elements these scanners can, in principle, be constructed by recording the interference pattern between two coherent wavefronts. However, there are several advantages to constructing these holographic scanners as computer generated holograms. The computer generated holographic scanner (CGHS) utilizes a digital computer to calculate and plot an appropriate fringe pattern which will cause the laser beam to scan the desired pattern. One important advantage to computer generating these scanners is that a recording media sensitive to the 10.6μm wavelength of CO_2 lasers is not needed. Additionally, computer generation allows the recording of scanners with complex scan patterns having varying scan rates and scan directions. These same scanners might be difficult or impossible to optically fabricate, but their fabrication becomes straightforward when using computer generation. Finally, CGHS are typically made binary. This binary nature allows them to be more easily converted to phase reflection holograms for use in CO_2 laser material processing.

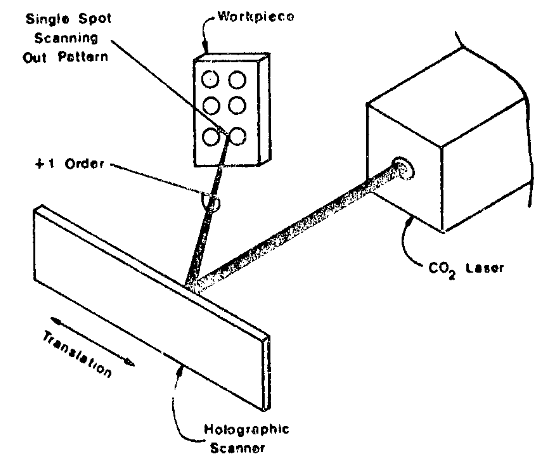


Figure 3. A reflective holographic scanner used to scan a single spot over the workpiece.

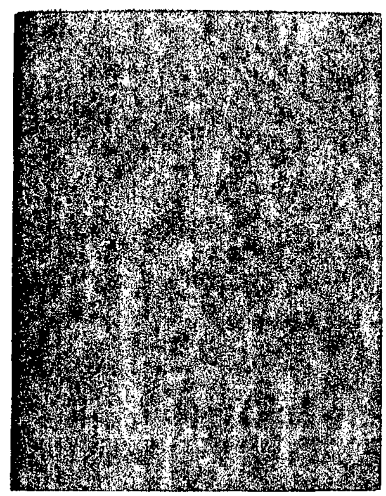


Figure 4. Reconstruction of a scanner with a He-Ne laser to scan the letters DC. The letters are about 1 cm. high.

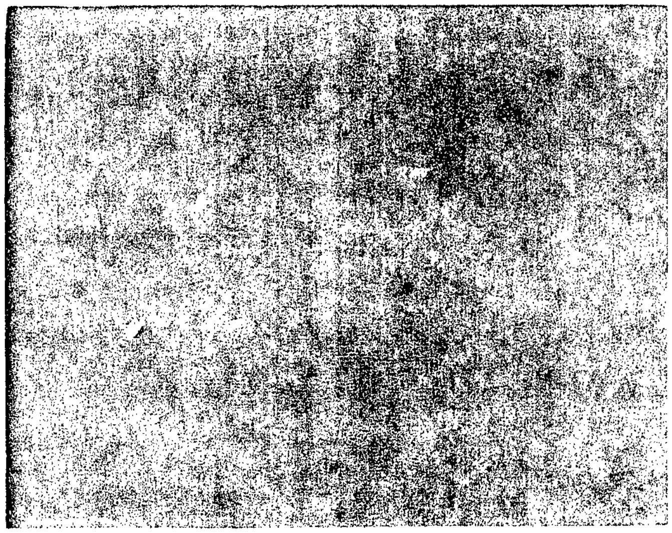


Figure 5. Reconstruction of a phase reflection scanner with an 11 Watt CO_2 laser. The image is engraved in Plexiglass.

Figure 4 shows a typical result when a scanner is reconstructed with a He-Ne laser. This scanner scans the laser beam over the letters "D" and "C". The letters are about one centimeter high.

The image shown in Figure 5 was obtained by reconstructing a phase reflection CGHS with an 11 watt CO_2 laser. This scanner had a first-order diffraction efficiency of about 30%, the images were reconstructed at a distance of 23 cm. from the CGHS. The maximum power density in the first-order image should be on the order of 1000 watts/cm^2. If the diffraction efficiency of this CGHS was increased to the theoretical maximum of 40.5%, and it was reconstructed with a 1000 watt CO_2 laser, the maximum power density in the first-order image would increase to 1.2×10^5 watts/cm^2. Furthermore, if this same scanner was reconstructed so the images are at a distance of 10 cm. from the CGHS, the power density would increase to 2.0×10^5 watts/cm^2. These power densities should be sufficient to perform a number of laser material processing operations.

PROGRAM OBJECTIVES - During the next ten months we plan to address the following issues:

1. Develop a technique for recording holograms in the visible and reconstructing at 10.6μm. This will require a procedure for balancing the aberrations introduced by the wavelength shift.
2. Study the effects of reconstructing the holograms with lasers that lase in higher order transverse modes. This is an important practical consideration since most high-power CO_2 lasers operate in higher-order modes.
3. Analyze new types of CGH to determine the optimum prodedure for this particular application.
4. Analyze image degradation in phase reflection CGH caused by distortion, approximations, and errors in the construction of the CGH.
5. Study the advantages of multi-level etching to determine if there are sufficient advantages over two-level etching to warrant development of the necessary fabrication procedures.
6. Develop a simple technique for constructing low to medium power density phase reflection holograms. Case Western Reserve University is developing rugged high power density holograms but there is a need to be able to quickly generate simple reflection holograms at Purdue to test new ideas.

DOCUMENTATION - None.

CONTACTS - Dr. Wai Hon Lee, Xerox Palo Alto Research Center, Palo Alto, California, 415+494-4238

DELIVERABLES - None.

COLLABORATORS - Zerox Corporation (Tentative)

HOLOGRAPHIC LASER MACHINING

Professor John C. Angus
Professor Robert V. Edwards
Professor Uziel Landau
Professor J. A. Mann, Jr.
Mr. Fred Coffield
Mr. Yezdi Dordi
Department of Chemical Engineering
Case Western Reserve University

PROGRAM OBJECTIVE - The purpose of this research is to determine whether computer generated, reflection holograms can be used with high power lasers for precision machining operations.

High power lasers have found applications in industrial processing. Typical uses include welding, drilling, scribing, cutting and surface hardening. These applications have made little use of the coherence properties of the laser light, but rather use the laser as an "energy hose". The usual scheme has the beam focused to a small spot which is then moved over the work surface by moving the workpiece or by moving the beam. The approach we are taking requires motion of neither the workpiece nor the optical components and potentially can be used to machine shapes of great complexity.

In simplest terms, we propose to put the laser power in the desired places on the workpiece by means of a reflection hologram. The hologram will be illuminated by a coherent beam of high power laser radiation. (In our case a CO_2 laser operating at 10.6 μm is used.) The real image generated by the hologram will fall on the workpiece, removing material selectively and simultaneously over the entire surface of the workpiece. Potential applications are many, including: part marking, scribing of complex two dimensional shapes, simultaneous drilling, welding or soldering operations, surface heat treatment of complex patterns.

The advantage of reflection holograms over imaging or transmission holograms is maximum utilization of laser power. No power is masked off and thus the only losses are heating losses in the hologram. These are typically less than a fraction of a percent. Further, the metal holograms can be cooled to minimize distortion due to heating.

Major technical problems include the development of economical, rugged holograms that can be used in practical settings and, secondly, achievement of more efficient utilization of the available laser power. Specifically, we will 1) develop holograms which will suppress the zero order spot and higher diffraction orders, 2) study means of initiating machining at lower total power densities, 3) develop alternate methods of hologram fabrication including electroplating, and 4) study hologram degradation.

Suppression of the zero order spot (putting the power in the desired image) needs to be attacked on two fronts. First, algorithms for efficient, low distortion holograms without zero order spots need to be developed. Coupled with that, we need a method to keep good tolerances on the fabricated holograms. The dimensional fidelity required to suppress the zero order spot is much higher than the tolerances required merely to make a good image.

PROGRAM ACHIEVEMENT - This project started on May 15, 1978. Research results achieved prior to the grant are summarized in two published papers referenced under the DOCUMENTATION section below.

Briefly, we have developed several methods, based on conventional integrated circuit technology, for production of rugged, binary reflection holograms. Special purpose Fast Fourier Transform routines are used to compute the hologram of the desired image. (In most cases we have used routines developed by Professor Neal C. Gallagher, Jr., of Purdue University). The hologram, usually a patchwork of black rectangles on a white field, is plotted with a Cal Comp plotter. A high contrast reduced photographic mask is made from the binary (black and white) hologram plot. In one technique a $\lambda/4$ thick layer of Al, i.e., 2.65 Å, is vapor deposited on a Si mirror blank. The Al is coated with a standard commercial photoresist and the mask is used to pattern the photoresist using conventional techniques. Subsequent etching of the Al through the patterned photoresist down to the Si substrate leaves the hologram imprinted on the surface as an array of rectangular raised mesas, $\lambda/4$ high, above the Si surface. (The negative, i.e., an array of rectangular pits, is equally effective because of the phase only nature of the image construction from the hologram.) The final step is the deposition of a very thin aluminum coating to insure uniform reflectivity.

Holograms produced in this and similar ways have been successfully used to form images with visible light (6328 Å He-Ne laser) and in the infra-red (10.6 μm CO_2 laser). Efficiency of the present devices is, however, not optimal. Excessive power appears in the central order spot and some additional power is lost in the higher order images. Furthermore, the fidelity of reproduction of the hologram on the reflector is not as good as desired.

RESEARCH RESULTS SINCE THE PROJECT START DATE - This grant has been in effect only since May 15, 1978. During the first two months of the grant we have initiated work on the fabrication of holographic reflectors by electroplating. Copper is electroplated onto copper mirror blanks through the patterned photoresist. This process has the advantage of providing a monolithic, rather than a composite, reflector and also holds the promise of much greater fidelity of reproduction of the hologram. Initial results

indicate pulsed plating techniques with careful control of current density can provide the desired quality of electroplate. We are also starting work on the electrochemical production of continuously modulated reflecting surfaces, which could potentially be used as grey scale reflection holograms.

Further work during the first two months of the project has involved power measurements using a series of existing reflectors and the development of a better method for the direct measurement of the depth of the surface features. Deviation in the depth of surface modulation from $\lambda/4$ degrades the diffraction efficiency. At the present time we only have indirect means of measuring the depth.

We have also made several attempts to product a ternary (three level) reflector. This research could lead ultimately to the production of reflection kinoforms, a type of multi-level reflector which constructs an image with no zero order spot and no multiple images.

PROGRAM OBJECTIVES - During the next ten months we plan to: 1) finish the development of a process for producing binary copper reflectors by electroplating, 2) continue work on electrochemically producing continuously modulated reflector surfaces, 3) product and test several reflectors using different types of holographic arrays, 4) continue work on development of multilevel reflectors.

DOCUMENTATION - The following two papers were published prior to the start of the present project.

Neal C. Gallagher, Jr., John C. Angus, Frederick E. Coffield, Robert V. Edwards, J. Adin Mann, Jr., "Binary Phase Digital Reflection Holograms: Fabrication and Potential Applications," Applied Optics, 16(2), 413-17 (1977).

John C. Angus, Frederick E. Coffield, Robert V. Edwards, J. Adin Mann, Jr., Robert W. Rugh, Neal C. Gallagher, "Infrared Image Construction with Computer Generated Reflection Holograms," Applied Optics, 16(11), 2798-99 (1977).

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DELIVERABLES - We have the capability of producing binary holographic reflectors on a routine basis. The starting point can be a black and white opaque plot of the hologram or, preferably, a mask of the desired dimensions.

COLLABORATORS - Our principal collaborators are the research group at Purdue University which includes Professors Donald W. Sweeney and Professor Warren H. Stevenson of the Department of Mechanical Engineering and Professor Neal C. Gallagher of the Department of Electrical Engineering. Technical assistance with silicon chips and other matters has been received from the Cincinnati Milacron Corporation of Cincinnati, Ohio (formerly Cincinnati Milling Machine Co.). Extensive collaboration also takes place between our group and the high energy laser group at the NASA Lewis Research Center in Cleveland.

GENERAL METHODS TO ENABLE ROBOTS WITH VISION TO ACQUIRE, ORIENT AND TRANSPORT WORKPIECES

Professors J. R. Birk and R. B. Kelley
Department of Electrical Engineering
University of Rhode Island

PROGRAM OBJECTIVE - Almost all manufacturing machines require oriented workpieces for proper operation. Workpieces are usually oriented by the human operators who feed these machines. However, the continued use of human labor will not lead to sufficient improvements in productivity. Furthermore, the cost of labor is increasing. Some workpieces can be oriented by mechanical feeders. Sometimes the orientation of workpieces can be preserved. If these approaches are not appropriate, industrial robots with vision may be used. The research problem is to find useful robot techniques to feed machines with workpieces supplied unoriented in containers.

Program objectives include the following:
1. Develop methods to acquire, orient and transport workpieces using a computer controlled arm and vision.
2. Develop methods to find the position and orientation of workpieces when they are in a bin or in a robot hand using data from TV cameras.
3. Develop a useful system architecture and experimentally demonstrate a robot feeding workpieces directly from a bin.
4. Transfer the results to industry.

PROGRAM ACHIEVEMENT - NSF support commenced on April 15, 1975. Substantial preparatory work was done prior to that date. The program achievements to be described here are for the period December 1976 through September 1977.

Visits to industry - Visits to local industries were made for the dual purpose of introducing our research interests to the manufacturing community and of gaining familiarity with the manufacturing issues relevant to our research. Many photographs of workstations were taken and samples of workpieces were collected. These visits were our primary method of interacting with local industry.

Definitions - Definitions clarify ideas within a research group. Definitions also clarify descriptions to facilitate the transfer of technology to industry. A set of definitions was developed relevant to research on general methods to enable robots with vision to feed machines with workpieces supplied in containers. Some of these definitions are listed below:

Workpiece - a unit quantity of material which is being processed.
Pose - position and orientation (usually of a workpiece).
Acquire - calculate how to move a robot arm to grasp, move the arm, and then grasp.
Transport - change pose without a collision.
Orient - gain pose information and then transport using that information.
Goal site - structure which receives and processes oriented workpieces.
System architecture - the physical structure and function of the following system components and their interrelationship: the robot arm, the computer, sensors including the TV camera and lenses, the sources of illumination, the supply of workpieces, and the goal sites.

Task hierarchy - A hierarchy of fundamental tasks and subtasks which must be performed by a robot to enable it to feed workpieces directly from a bin was developed. This allowed the research problems to be identified and ensured that a complete solution would be provided. An abbreviated version of the task hierarchy is listed below:
1. Acquire a transportable workpiece from a bin.
   - A. Gain information about the poses of workpieces in a bin.
     - i. Relate pose to image features.
   - B. Choose a hand-workpiece relationship.
   - C. Move and grasp the workpiece.
2. Decide if the hand-held workpiece is transportable.
3. Transport the workpiece to the goal pose.

Acquisition algorithms - One of the major subtasks of acquiring a transportable workpiece is to gain pose information on workpieces in a bin by relating image features to pose. To provide distinctive image features and make recognition insensitive to a slight overlap of workpieces, software was developed for a set of features which are based on a portion of a single workpiece image. These are extracted from a binary image and thus function particularly well when clean edges exist for workpieces in a chute or for flat surfaces under directed illumination. The features are derived from the peripheral pixels of holes and globs. The features are straight line segments, corner angles, hole centroid, hole area, and maximum/minimum distances from hole periphery to centroid. An orientation classification experiment on a 15^{o} sampling grid with workpieces obscured as much as 25 per cent always gave correct classification. However, sometimes one or two adjacent orientations were equally well matched.

Hand-workpiece relationship - The problem of estimating the hand-workpiece relationship was divided into two parts because different solutions are appropriate for coarse and fine decisions.

1. The suggested procedure for finding the major subdivision of the pitch-roll sphere to which the orientation of a workpiece belongs is to choose the sampled appearance which most closely matches the current image.
2. The suggested procedure for precisely identifying the orientation and position of a workpiece is to relate appearance perturbation, measured by image features, to pose perturbation. This relation can be established during instruction at several "visual check poses."

Hardware development - To conduct general experiments on workpiece orientation, a new three axis rotary joint wrist was designed. It incorporates improvements suggested by experience with the predecessor wrist unit. The new wrist uses a housed encoder attached to the output shaft via antibacklash gearing. Cylindrical shell construction is used for strength and alignment of the shafts, gears, and motor. Tachometer feedback is incorporated to facilitate hardware servo control. Wrist geometry is designed to minimize the effects of gravity by having it point down and by limiting long moment arms.

Software development - Software is the vehicle for carrying concepts and procedures from the idea to the experimental world. This project typically generates more than 10,000 lines of assembly language code per year. Our software concerns are the efficient generation of software to support our experimental work, documentation so that duplication can be avoided, and ease of reuse and modification of existing software for new experiments. Software standards for the description of programs and for data structures, especially data blocks and public stacks, were developed.

RESEARCH RESULTS SINCE THE SEPTEMBER 1977 REPORT - The work since September 1977 is described under the following headings: first integrated robot system for feeding workpieces from bins; representing images of workpieces; a theory for automating symmetry determination; alternative system architectures; and gage for measuring workpiece pose.

First integrated robot system for feeding workpieces from bins - An experimental robot system has been developed which is designed to acquire unoriented workpieces from a bin, analyze workpiece orientation in the hand, and then orient the workpiece on a goal site. An overview of the system can be seen in Fig. 1. The problem of acquiring unoriented workpieces was solved by integrating a visual algorithm with the design of a gripper. The difficulty of visually computing the orientation of workpieces in a bin and the

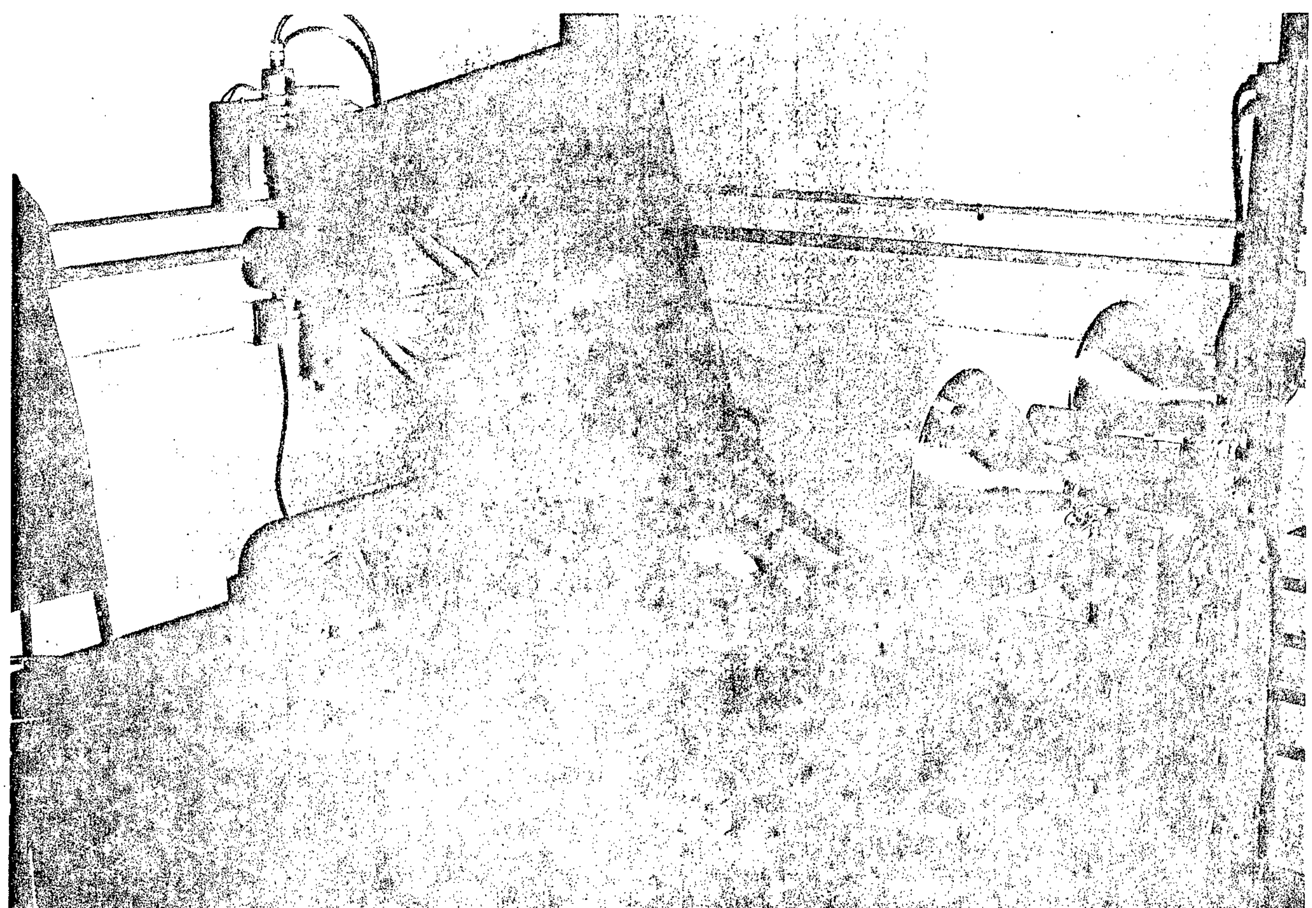

Fig. 1. Overview of an experimental integrated robot system for ˉ ed.ng workpieces from bins.

difficulty of avoiding collisions between the gripper and workpieces led to the concept of building a gripper which would adapt to surface orientation. Such a gripper was designed using a vacuum cup that is connected to a piston thru a spring. When the piston is released, the spring allows the vacuum cup surface to adapt to surface orientation, as shown in Fig. 2. When the piston is locked, the workpiece can be held rigidly, as shown in Fig. 3. To select a location for the arm to descend with the gripper unlocked, a simple vision algorithm was found to be quite successful. A camera on the arm can take a picture from directly above the bin. This image is analyzed to locate square regions with intensity values all above a threshold. This algorithm tends to select uniformly reflecting surfaces that are close to horizontal. It avoids sending the gripper to regions in the bin in which there are holes, slots, or no workpieces. A TV camera picture of a bin of drapery brackets is shown in the upper part of Fig. 4. In the lower part of Fig. 4 is a binary picture formed from the gray scale picture. Superimposed on this binary picture are a few squares which satisfied the square region criteria. Experiments with several workpieces indicate that 60 to 80 per cent of the attempts made to grasp a workpiece are successful.

Once a workpiece is in the robot hand, the workstation camera can examine it. By matching features learned during instruction for the different workpiece states in the hand, the state can be computed, along with translation and rotation on the vacuum cup surface. For the experimental system, local binary features are used, such as corners. The upper left quadrant of Fig. 5 shows a gray scale image. The lower left quadrant shows a binary image. The lower right shows peripheral pixels with holes and corners labeled. If two states of the workpiece in the hand yield nearly the same appearance, the arm moves to a verification pose where simple image features, such as centroid or area, can be used to distinguish states. The image at a verification pose is shown in the upper right quadrant in Fig. 5. Using knowledge of workpiece orientation in the hand, the workpiece is placed either on an insertion tool or a regrasping station. When it is placed at these two goal sites it always has the same position and orientation. Experiments have shown that the piece can be positioned within 1/4 inch and 5 degrees, worst case.

Once a piece is placed at a goal site with a fixed orientation, many options exist to transfer the piece to a machine, including the use of fixed stop arms. For the experimental system, a piece placed on the insertion tool is brought to a gage by having the robot pick up the insertion tool and go thru a fixed motion. If the piece is at the regrasping station, the arm grasps the insertion tool, which grasps the piece, as shown in Fig. 6. Then the arm goes thru a fixed sequence of motions to bring the piece to the gage.

The engineering significance of this experimental system is that, as far as we know, it is the first integrated robot system for feeding workpieces which are completely unoriented in bins. The ability to orient and place workpieces on the goal sites, the technically difficult problem, has been operational for two months. Transferring the parts to the gage automatically should be completed soon. Currently the time to transfer a piece to a goal site is about 30 seconds for a piece that requires a verification pose. We can expect significant reductions in cycle time as the system matures.

The system has general utility because it can readily be reprogrammed to handle different workpieces. Feeding parts directly from a bin eliminates the need for mechanical parts presentation systems which add cost to the system and are often workpiece dependent. If the technology exists to feed from bins, then

Fig. 2. A vacuum cup gripper demonstrating surface adaptation.

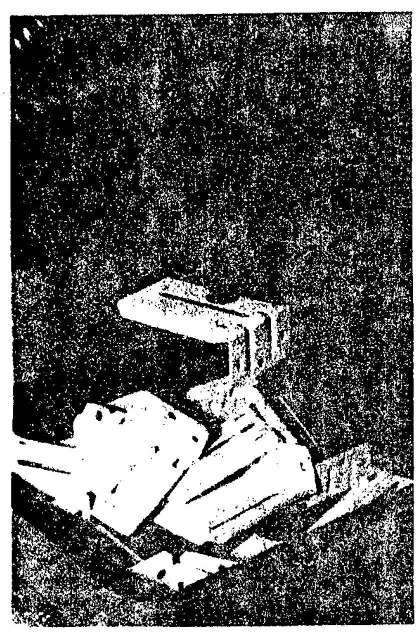

Fig. 3. The same vacuum cup gripper, when locked, holding the workpiece firmly.

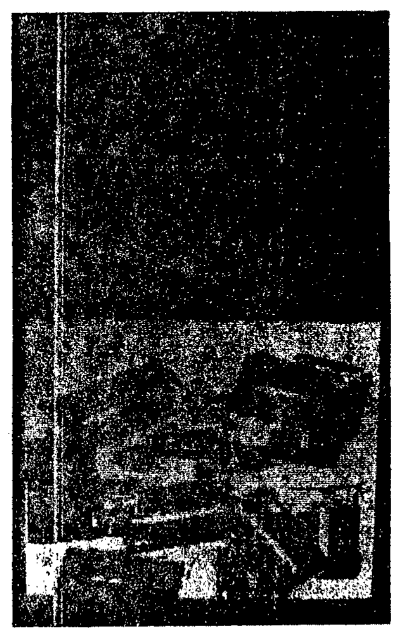

Fig. 4. Image analysis used to direct the surface adapting vacuum gripper.

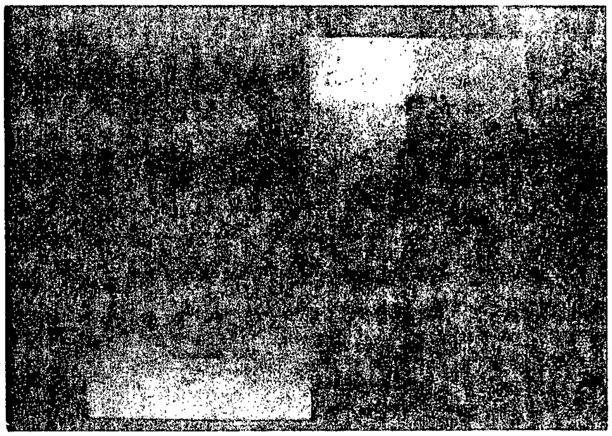

Fig. 5. Image analysis of the workpiece in the robot hand to determine the pose of the workpiece relative to the robot hand.

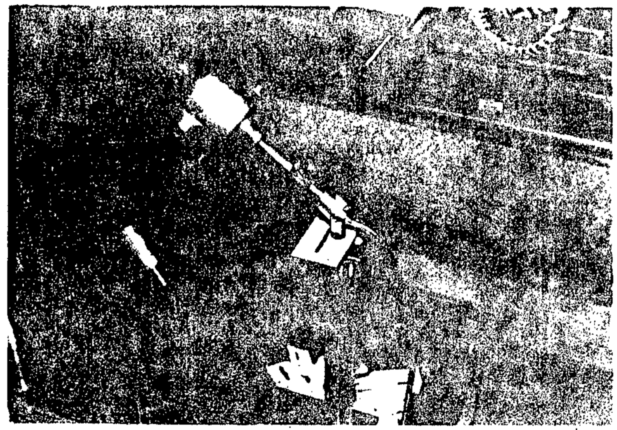

Fig. 6. An insertion tool attached to the robot hand, grasping an oriented piece at a goal site to transport it to a gage with the pose required for measurement.

it will also be possible to feed parts supplied in just about any other way. However, if a technology is developed which exploits the constraints of workpieces in certain presentation systems, then it may not be possible to apply that technology when the constraints can't be imposed.

Representing images of workpieces - A major research problem associated with acquiring, orienting and transporting workpieces is finding good ways to represent images of workpieces. A good representation yields a small set of numbers which characterize the array of intensity values, yet permit decisions to be made, such as determining the pose of a workpiece. In the past we have explored global binary features. These features change if any part of the binary picture changes. They are useful for many workpieces with stable resting states, but generally can't be used when workpieces overlap in an arbitrary way.

During the past year, the software to compute local binary features was upgraded. These features may be used to compute workpiece pose when a modest amount of overlap exists, e.g., 25 per cent. Thus these features might be used for computing the pose of workpieces in a thin layer, such as would occur on a chute. Problems with binary images are that they frequently provide inadequate data to make decisions about workpiece pose and the image can change significantly if a change in lighting occurs at the workstation.

During the past year, a set of local gray scale image features was developed. Although local computation makes them useful for overlapping workpieces, the chief advantage of local computation is that these features can be computed in hardware. The local gray scale image features developed are based on the histogram of the gradient directions for all the pixels of an approximately circular region about a pixel. By testing for strong peaks in this histogram, edges can be located. Double peaks in the gradient direction histogram occur when corners are present. Wide peaks occur when rounded edges are present. To reduce the number of feature points, wide peak and second peak detectors must satisfy the test of being locally optimum in a circular region. Strong peak detectors are required to pass a test of being locally optimum along the direction of the dominant intensity gradient. The parameters used to control the feature extraction process can be optimized by varying them until the output matches the labeling superimposed on test images by a human. Tests indicate that this type of feature will be useful in image representation, although more work is required to explore their potential adequately.

A theory for automating symmetry determination - Workpieces which present the same appearance to a TV camera for two orientations are a special problem for an orienting robot. If the robot knew the workpiece to be symmetrical, it would know that it doesn't matter that two or more sides appear the same and could proceed directly to transporting the piece to a goal site. On the other hand, if the robot doesn't know about the piece's symmetry, it would have to try another view by changing the orientation between the workpiece and the TV camera. It might find an unambiguous view for an unsymmetrical workpiece, but the process would repeat for a symmetrical piece.

A method has been developed to analyze equal appearances from many views of an object to automatically determine rotational axes of symmetry. Mirror symmetry is no problem because mirror symmetrical images are distinguishable. To propose an axis of symmetry, two orientations with equal appearances and image direction, i and k, are related by a symmetry transformation, $^{i}T_{k}$, using 3×3 cosine matrices between axes: $^{i}T_{k} = (^{o}T_{i})^{-1}\,{}^{o}T_{k}$. If the image directions don't match, it is possible to adjust a matrix using the angle between the direction of the two images.

The proposed axes of symmetry are verified by a matching procedure which takes into account the appearance for all sampled orientations. One sampling scheme used for experiments has 38 samples over the pitch, roll sphere. Each sample orientation, m, is operated upon by the symmetry transformation to find

the orientation, n, after rotation about the axis of symmetry by the following formula, ${}^{o}T_n = {}^{o}T_m\ {}^{i}T_k$. The sample orientation closest to n is examined to see if it has a similar appearance to orientation m. If so, support is gathered for the validity of the proposed symmetry transformation. A proposed symmetry transformation is only verified if nearly all orientation samples map into other orientations with a similar appearance.

The theory for automatically identifying rotational axes of symmetry has been verified by exercising the theory on a sample problem. This experiment indicated that true axes of symmetry receive strong confirmation from the matching procedure, whereas axes of symmetry proposed by circumstantial equivalent appearances are readily rejected.

Alternative system architectures - Although the system architecture of the experimental orienting robot was selected for tests, alternative approaches have been identified. Various methods of presenting workpieces were considered. Desirable properties of a presentation system are: pieces are placed where they are easily accessible, pose uncertainty is reduced, pieces are isolated, pieces that are not easily transported to a goal site are recycled, and it should function for many different pieces.

One way of constructing a device, which might satisfy all these requirements, would be based on a series of conveyor belts operating at different speeds, with the slower ones dropping pieces onto the faster ones. The use of presentation systems is an option for engineers in industry concerned with applications. In general, presentation systems add cost and occupy workspace, but they simplify and make faster the process of acquiring workpieces.

Other system architecture components worth considering relate to the problem of transporting a workpiece with arbitrary orientation in the hand. One component which is not demonstrated in the current URI experimental system is an orienting station. An orienting station can receive a workpiece, change its pose, and release it. Thus when an arm can't transport a workpiece to a goal site, it could bring the arm to a reorienting station which would permit the hand-workpiece relation to be changed.

Gage for measuring workpiece pose - The URI Mark IV robot uses vision to position and orient workpieces in space. To evaluate the accuracy with which this job is performed, a gage was built. The gage can measure pose and pose errors for workpieces having a right trihedral corner, as shown in Fig. 7. Two of the probe pairs are in contact with the workpiece, one probe pair is still retracted.

The probes of the gage define a reference coordinate system. The tips of each probe pair move along parallel paths; the probe pairs lie in mutually perpendicular planes. The gage coordinate system origin is the common intersection point of the three planes. The gage coordinate system axes are along lines defined by the pairwise intersection of the three planes. To establish a nominal workpiece pose relative to the gage, a workpiece is inserted into the gage, six probe readings are taken and the gage-nominal pose relationship is computed. Thereafter, when a workpiece is inserted into the gage, the six readings permit the gage-actual pose relationship to be computed. Relative to the nominal pose, the pose error is given by the nominal-actual pose relationship which is easily computed using the standard homogeneous matrix representation for the poses. A straight forward computation results in evaluating the expression for the pose error matrix

$$ {}^{n}T_a = ({}^{g}T_n)^{-1}\ {}^{g}T_a $$

which was obtained from the equality

$$ {}^{g}T_a = {}^{g}T_n\ {}^{n}T_a $$

where:

${}^{g}T_a$ = gage-actual pose relationship matrix,

${}^{g}T_n$ = gage-nominal pose relationship matrix,

${}^{n}T_a$ = nominal-actual pose relationship matrix.

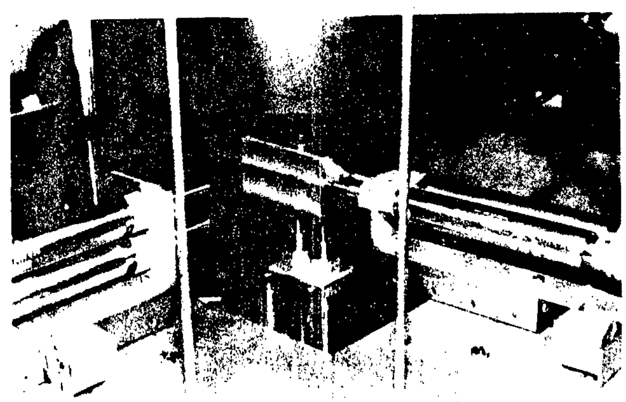

Fig. 7. A gage with six probes that can measure the six values of pose for a piece with a right trihedral corner.

Error statistics can be collected on the rms position and rms angular pose error without extracting the error components from the entries of the pose error matrix ${}^{n}T_a$. The homogeneous matrix entries corresponding to origin coordinates are the position error terms. Thus rms position error is the square root of the average of the squared position error terms. The rms angular pose error is obtained from the sum of the entries corresponding to the cosines between corresponding X, Y, and Z coordinate axes (the trace of the rotation submatrix). For small error angles (less than 5^o), the rms angular pose error is the square root of the quantity: one minus the average trace entry.

Gage specifications are as follows. Mechanically, the DC-LVDT probes have ranges of $\pm$ 1/4 inch, maximum spring loads of less than 3 ounces, and have spherical contact points with a diameter of 1/32 inch. The probes are carried on slides with a travel of 3 inches and are held in the measuring position by magnets with a force of 5 pounds. Electrically, the DC-LVDT probes require $\pm$ 15 V at $\pm$ 20 mA, have a sensitivity of 40 V/inch (full range is $\pm$ 10 V), and a deviation from linearity of less than 25 mV which equals

1/4 per cent of full range. The A/D converter gain was adjusted so that the least significant bit corresponded to 1/2 mil (which equals 20 mV electrically). This results in a probe reading of sign plus 9 significant magnitude bits.

Probe reading error contributions are: electrical linearity = 0.6 mil, A/D conversion = 1/4 mil. To obtain less than 2 mil computed position coordinate errors, probe reading errors must be less than 1 mil; this also gives angular rotation errors of less than 1/8 degree. Thus, mechanical errors can contribute 0.15 mils error. There are three independent sources of mechanical error: probe parallelism and plane perpendicularity. For each source to contribute less than 1/20 mil (equal contributions), parallelism must be better than 1 1/4 degrees, perpendicularity between planes must be better than 1/4 degree.

Such a gage may be used in various ways.

1. The gage can be used to measure the performance of the robot arm itself. By attaching a right trihedral corner to the robot, repeatability, accuracy and incremental motions can be investigated.
2. Other orienting and positioning systems can be measured. If the piece doesn't have a right trihedral corner, give it one for use in the gage. Fewer than six degrees of freedom can be measured; mount the probe sets on ball-jointed holders to get the measurements desired.
3. Periodic workpiece pose gaging monitors variations in workpieces or changes due to the handling system.
4. Automatic gaging under computer control is an exciting possibility for obtaining highly precise placement of workpieces. Preliminary procedures can be used to get the workpiece into the restricted measuring range of the gage. The measured workpiece pose can be used to accomplish critical placement tasks.

The gage is a versatile measurement tool.

PROGRAM OBJECTIVES - For the next ten months, work will continue on three main themes: estimating workpiece pose, acquiring workpieces from bins, and transporting workpieces. Specific research problems which will be addressed are: improved representations for images, improved representation for workpieces, pose estimation for six continuous degrees of freedom, hardware image processing for local gray scale features, vision for acquisition, and general purpose hand designs which simplify acquisition, orientation determination, and transportation. Other activities in the near future include: improving the quality of image data, giving velocity control to the Mark IV arm, studying alternative system architectures, and improving the performance of the experimental system that feeds workpieces from bins.

DOCUMENTATION - Generated since September 1977:

1. J. Birk, R. Kelley, L. Wilson, V. Badami, T. Brownell, N. Chen, D. Duncan, J. Hall, H. Martins, R. Silva and R. Tella, "General Methods to Enable Robots with Vision to Acquire, Orient and Transport Workpieces," Fourth Report, Grant APR74-13935, University of Rhode Island, July 1978.
2. L. Wilson, "Selective Acquisition of a Workpiece from a Chute by a Robot Using Image Processing Techniques," M.S. Thesis, University of Rhode Island, 1978.
3. R. Kelley, J. Birk, and R. Silva, "Identification of Object Symmetry from Multiple Views," IEEE Computer Society Conference on Pattern Recognition and Image Processing, Chicago, Illinois, May 31 - June 2, 1978.
4. J. Birk, R. Kelley, and L. Wilson, "Acquiring Workpieces: Three Approaches Using Vision," Eighth International Symposium on Industrial Robots, Stuttgart, Germany, May 30 - June 1, 1978.
5. J. Birk, R. Kelley, N. Chen, and L. Wilson, "Image Feature Extraction Using Diameter Limited Gradient Direction Histograms," IEEE Computer Society Workshop on Pattern Recognition and Artificial Intelligence, Princeton, New Jersey, April 12 - 14, 1978.
   Also submitted for publication in the IEEE Transactions on Computers.
6. R. Kelley, J. Birk, and V. Badami, "Workpiece Transportation by Robots Using Vision," Second North American Industrial Robot Conference, Detroit, Michigan, October 31 - November 3, 1977, SME Paper MS77-746.
   Also published in The 1978 Manufacturing Engineering Transactions, SME, Dearborn, Michigan.
7. R. Kelley, J. Birk, and L. Wilson, "Algorithms to Visually Acquire Workpieces," Seventh International Symposium on Industrial Robots, Tokyo, Japan, October 19 - 21, 1977.

CONTACTS - Project personnel, September 1978: J. Birk, R. Kelley, V. Badami, T. Brownell, N. Chen, J. Crouch, D. Duncan, J. Hall, H. Martins, R. Silva, R. Tella.

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DELIVERABLES - Reports, software, electronic and electrical diagrams, and mechanical drawings are available upon request.

COLLABORATORS - A variety of local companies have supplied us and will continue to supply us with information about machines which are loaded with workpieces supplied in bins or chutes. Some of these companies include Brown and Sharpe, Bostitch, Gorham, Uncas, Kenney, Welsh, Sheldahl, Dixon, Amtrol, and Tupperware. During the next year, we are interested in seeking advisors from industry who will assist in making decisions about the priority of various research problems.

ADVANCED INDUSTRIAL ROBOT CONTROL SYSTEMS

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PROGRAM OBJECTIVE - The objectives of this research are to extend the flexibility and usefulness of current industrial robots and to provide a solid base for future advanced systems based on computer control techniques and dynamic manipulator models. In order to meet these objectives we are developing a control scheme based on manipulator motion in joint coordinates, yet capable of working on moving assembly lines and accepting visual position information. A main feature of this approach is the greatly reduced real time computational requirements over systems which control motion directly in cartesian coordinates.

Within this joint motion control scheme we have the following research objectives.

To develop a simple language in order to test various manipulator control and task primitives.
To provide compliance to external position constraints, such as in mating parts during assembly.
To study various approaches, both on-line and off-line, to motion optimization with respect to time.
To develop a system suitable for implementation on currently available microcomputers.

In parallel with the manipulator research we are also investigating a vision system to detect, identify and locate objects on a moving conveyer. This work is based on a continuing investigation of three-dimensional scene analysis based on a two-dimensional projection.

The mode of attaining these research objectives is based on dynamic and kinematic models of the manipulator which provides a solid base on which to build a manipulator control system. Compliant tasks, in which the manipulator adapts dynamically, are described in terms of degrees of freedom in a working coordinate system; in this work, joint torque control will be employed to provide the required compliance. Speed of operation of the manipulator will be optimized both directly and in terms of a model. This work will be integrated into a manipulator control language; the primitive instructions will be carefully chosen to provide a consistent language to facilitate programming and as a target output language for future high level languages. This manipulator control language will account for the dynamics of the manipulator and will provide optimized and compliant motions, freeing the user, or high level language, from these considerations.

PROGRAM ACHIEVEMENT - Major accomplishments for the first three months of this grant, through September 1977 are:

A. Motion in Joint Coordinates - The initial theoretical development work was performed in the area of motion in joint coordinates. While robot tasks may be described in terms of cartesian coordinates or in joint coordinates, robots are more simply moved in joint coordinates. Given two positions close together in space, a coordinated motion in joint coordinates from one position to the next is a differential approximation to a true straight line cartesian motion. Over large distances coordinated motion in joint coordinated motion in joint coordinates is as predictable as straight line cartesian motion. The computations necessary to move a robot in joint coordinates are only those necessary to provide for the coordination of the joints. When robots are to work on moving assembly lines, however, the change in relative position between the robot and its work must be taken into account. This may be done by describing the task in cartesian coordinates of the robot end effector, to which the relative displacement of the line is added. We describe the conveyor in terms of an array of cartesian positions; the task is described with respect to the conveyor. These two descriptions may be combined to obtain task positions with respect to the manipulator for a discrete number of conveyor positions. These positions may then be transformed into corresponding joint coordinates. For any given tracking task joint coordinates for two adjacent positions are obtained; one for a position the conveyor has just passed and the other for a position it has yet to reach. Interpolation in joint coordinates, as a function of conveyor motion, between these points then provides for conveyor tracking. For a typical tracking task an array of 32 transformations is sufficient to provide for tracking to within nominal robot tolerance.

B. Minimum Traveling Time - Conventional manipulator control systems are designed in such a way that the manipulator stops at the end of each path segment. For motions make up from a number of path segments this results in an inefficient operation. By eliminating the need to stop at the end of each path segment and by ensuring that the manipulator moves at maximum velocity and acceleration, the traveling time can be reduced. These requirements as well as other physical constraints are expressed as a set of inequalities so that linear programming techniques can be applied in order to optimize the motion with respect to time.

RESEARCH RESULTS SINCE THE SEPTEMBER 1977 REPORT

A. Software for the Stanford Arm - The Stanford Arm has been interfaced to a COMSTAR industrial microprocessor system; and the interface, analog conditioning circuits, and power amplifiers have all been checked-out. The microprocessor system has in turn been interfaced to the Advanced Automation Research Laboratory PDP 11/45 computer through a bi-directional 16 bit bus. The bus and bus protocol software have been developed and checked-out. A sixty hertz clock has been added to the microprocessor system to provide manipulator state information to the PDP 11/45 at servo rate. Servo routines run in the 11/45 in response to the microprocessor interrupt and compute motor drive voltages which are transmitted back to the microprocessor system. Programs enabling communications between the arm and microprocessor and between

the processor and PDP 11/45 have been debugged.

B. Joint Motion Control Software - A joint motion control scheme which provides for coordinated motion in joint coordinates, controlled velocity through intermediate path-points, and cartesian or rotary conveyor tacking has been simulated in PASCAL and is being transferred to the PDP 11/45.

The system, known as PAL, will run under a UNIX operating system and is being coded in 'C'. The system is in three modules: an editor/scanner, a teach module and an execution module. The editor/scanner module will allow a user to create procedures in PAL, read in such procedures from an external file, edit the procedures, check for syntactic errors and compute transformations while parsing the procedures, and to write all procedures into an external file. Procedures are stored in an internal form bearing a one to one correspondance to the source text. The source text is replaced by a sequence of symbols with values stored in a symbol table.

The teach module will be capable of single stepping through a PAL procedure. If positions are undefined the manipulator will be placed under control of a joy-stick and the operator requested to move the manipulator to the correct spatial position, (teaching by doing). If the position is defined the manipulator will be moved there slowly under computer control. Auxiliary transformations representing such relationships as tools, grip position and manipulator placement are defined symbolically. The positions defined by teaching are recorded automatically by ammending the transform declarations to include initialization values. On teaching, only those positions through which the manipulator must pass need to be taught. Statements in the PAL procedure referring to compliance will modify the joy-stick control to provide the necessary compliance such that those positions requiring compliance (such as a part insertion) can be attained. The third module provides for program execution. Its input is a syntactically correct procedure with all positions defined in intermediate symbolic form. It provides for high speed motion with continuity of velocity and compliance through intermediate points. The system can work in moving coordinate systems and accept visual input information.

C. Optimal Coordinated Motion Control - It is important to be able to drive the manipulator in such a way as to obtain smooth and coordinated motion in a minimum of time. By coordination we mean driving the arm so that all joints traverse their required angles or distances in the same amount of time. For small motions this is a good approximation to straight line motion.

While it is possible to move all joints as a coordinated function of time, such functions are based on a model of the robot arm and this results in motion slower than that possible. Driving the joints individually with a PID (position integral derivative) controller results in fast motion but is totally uncoordinated. In this work we try to capture the fast motion of the latter with the coordination of the former.

A typical servo system for an industrial robot consists of PID controllers using position and velocity error signals to determine the motor drives for a given motion. This approach has worked well and is fast, but does not provide coordinated motion defined above.

To accomplish coordination we propose to have to related servo systems. The first servo, which we will call a joint servo, is similar to the one referred to above and provides for minimum time. The second servo, which shall be referred to as a coordinator servo, uses the relative position and the rate of change of relative position to determine the motor drives. (Figure 1). By relative position we mean the proportion of the trajectory the individual joints have traveled. In other words, if a joint is to travel 60° and it currently has traveled 10° its relative position is 1/6. These calculated values will be called coordination factors h. It can be seen that the values of h will be between 0 and 1. These values are calculated for each joint every sample period (1/60 second). The joint with the smallest h value will be the joint which is farthest behind for that sample period.

The determination of the slowest joint is difficult and the error has been calculated in a number of different ways with varying degrees of success. The current method takes the difference between the joint's h value and the weighted mean of the slowest joints. Only those joints with coordination factors less than the average coordination factor contribute to the average in the next sample period. Thus if there is one joint that is predominately slow the weighted sum reduces to the minimum value of the coordination factors.

If the relative position error is less than zero this implies that the joint is a slow joint and the joint servo is used. If the error is greater than zero the joint is ahead of the average and must be slowed down. This is accomplished by calculating where the faster joints should be if they were the same proportion of the distance through their motion as the slowest joint. This position is obtained by multiplying the average h value by the total change of position for that joint. This value and its rate of change are used as the error signals for the coordination servo (Figure 1). The resulting drive will have a sign opposite to that of the drive from the large scale servo. Therefore, when the two are added the drive will be reduced and any joint that is ahead of the slowest joint will be slowed down. This will make the faster joints track the slowest joint, while moving at the speed of the slowest joint which is as fast as the arm can move.

To date a series of simulation programs have been written in Fortran on the PDP 11/70 system.

The next step in the process will be the implementation of the coordination control system on the arm. This will be done in the next few months.

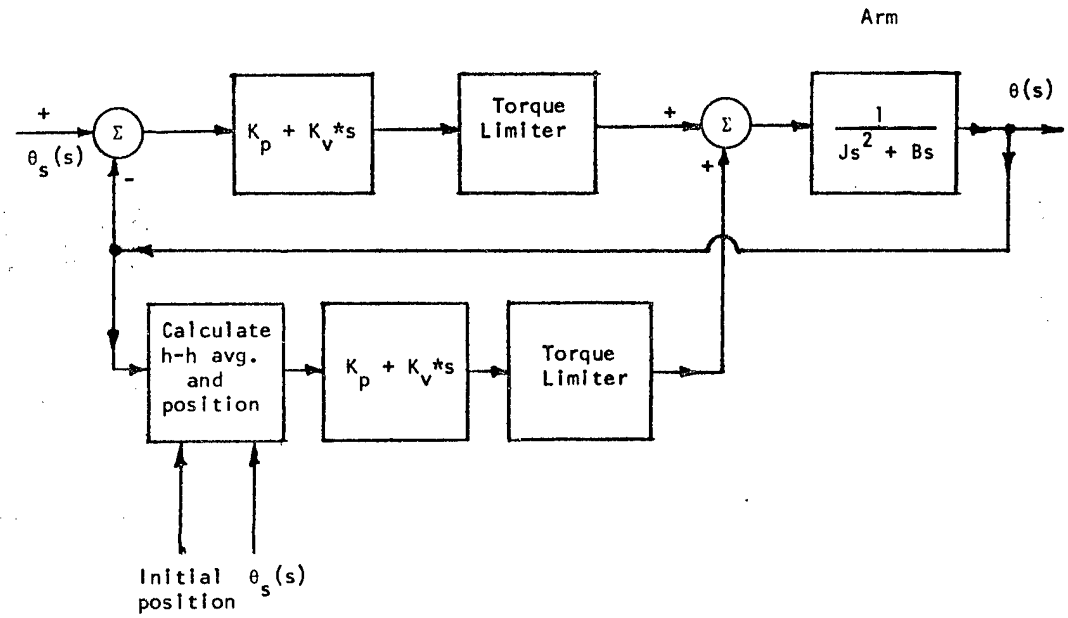

Figure 1

Joint and Coordination Servos

D. Linkwise Model of a Manipulator - To accomplish the objective of extending the flexibility and usefulness of current industrial robots, it is desirable to drastically curtail the computing time for the on-line control signals. Thus, a mathematical model was developed for the manipulator, which describes the dynamic behavior of each link and then combined to express the relationship between forces and moments at each successive link. The derivation of the model is based on the concept of frame of reference for moving coordinates. By the use of Coriolis' theorem, the model includes centrifugel and coriolis accelerations in addition to the gravity loading terms.

In using dynamic models for the design of control systems, it is important that the model be accurate enough so that the resulting control algorithm performs adequately. In other words, if the model is not a close enough approximation to the real system, then the response of the controlled system may not be very close to the expected response and in fact may be unstable. In modeling a mechanical arm, there are three components which make up the forces or moments at each link. These are due to joint accelerations, joint velocities, and gravity. Forces due to friction in the joints are also a component but are not included in this analysis.

An analysis of the relative magnitude of each of the components of the joint forces or moments was performed for the Stanford arm. In the analysis two typical trajectories were executed and then each component of the forces or moments at each joint were plotted versus time. The results showed that all three components of the forces and moments are equally important.

We shall compare the three models that have been developed for the analysis and control of the Stanford model arm. As an example we picked q_i=0.2, $\dot{q}_i$=1.0, and $\ddot{q}_i$=1.0, for i-th joint i=1,...,6, and then computed the resulting joint forces and moments using three models: viz, Hartenberg-Denavit [1,2], Bejczy [3], and the new recursive that we have developed. The computing times on the PDP 11/45 are summarized as in Table 1.

Table 1. List of time to compute joint forces and moments on the PDP 11/45 for various models.

Model	Language	Computation Time
Hartenberg-Denavit	Fortran	7.9 sec.
Bejczy	Fortran	0.0025 sec.
New Recursive	Fortran	0.0335 sec.
New Recursive	Floating Point Assem.	0.0033 sec.

From Table 1, it is seen that only the model developed by Bejczy and the new recursive model written in

floating point assembly language are fast enough to be computed every sample period of 1/60 second.

The outputs from the various programs are listed in Table 2 in which the new recursive model and the Hartenberg-Denavit model are theoretically exact models while the outputs generated by Bejczy's model include only the gravity terms and local joint accelerations. As can be seen from Table 2, excluding the velocity terms can cause significant errors in computed forces and moments.

Table 2. List of outputs for different models. Units are newtons for joint 3 and newton-meters for the remaining joints.

Model	Joint Forces or Moments					
	1	2	3	4	5	6
Hartenberg-Denavit & New Recursive	- .959	-3.61	-54.7	.1092	.1958	-.002
Bejczy	1.488	1.286	-55.8	.1516	.3775	.0204

PROGRAM OBJECTIVES FOR NEXT PERIOD

A. PAL System - We will continue the development of PAL system and bring up all three components (EDIT, TEACH, EXECUTE) on the 11/45 operating under the UNIX system and running the Stanford Arm. We will then evaluate the system segment it, and prepare it for transfer to an LSI/11 microprocessor.

B. Optimized Coordinated Motion - We will continue the development of the Optimized Coordinated Motion Control scheme, and merge it with the time controlled coordinated motion already provided in PAL. This will provide for optimized coordinated motions with velocity controlled trajectory segments. We will further extend this system to provide coordination with external machinery, such as presses. In this case the press, although uncontrolled, will appear as the slowest joint and will coordinate the motion. Such a system could provide for much closer coordination than present interlock schemes. This form of close coordination could result in significant time savings.

C. Compliant Motion - PAL primitives for compliant motion will be developed and included in the language together with the necessary algorithms for force and torque transformations between coordinate systems. The investigation of torque servo loops will continue with experimental verification using a single joint manipulator.

D. Parallel Processing for a Manipulator - To curtail the on-line computing and processing times for the linkwise model, a scheme will be developed for manipulator control using a microcomputer system. The overall manipulator control problem will be segmented into suitable subproblems so that the computational load can be distributed evenly.

E. Vision - The visual experimentation will be performed with a GE 128 X 128 element, solid-state video camera. A scheme will be developed which is based on the perspective transformation using syntactic approach for determining point - to - point correspondence between a two-dimensional projected pattern and a given set of three-dimensional model of known geometries. The on-line determination of 2D to 3D correspondences is achieved via tree matching.

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INDUSTRIAL ASSEMBLY PART MATING STUDIES

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GENERAL — The long range goal of this project is twofold, namely: 1) explore the new concept of force sensing at the interface when parts intersect during the process of assembly and, 2) to transfer this knowledge to industry.

The program has four main facets this year: 1) part mating theory; 2) experiments; 3) industrial applications; and 4) remote center compliance (RCC) theory. Early part mating analysis was limited to rigid devices with fairly simple geometry combined with carefully specified and located compliances. Out of this work came the unique Remote Compliance Center idea. Recently this idea has been developed for passive systems which are just now finding application in special machines where part variation has proved formidable. Simple RCC systems coupled with analog force measurement displays are a positive aid in low volume manual assembly of precision parts to avoid part spoilage and to allow a reproducible process. Theoretical analyses of press fits and of RCC deflections under large static and dynamic loads are in progress.

To date four industrial firms are currently exploring these techniques in their assembly problems. A fifth is more interested in the application of part mating science to the design of their products. This has resulted in extending the analysis to non-rigid pieces and pieces of very complex geometry. The extension of this work to other products offers design systematization in areas not previously thought possible.

PROGRAM ACHIEVEMENT — The principal program achievements have been the development of an integrated scientific knowledge base, both for categorizing assembly tasks and determining new machine configurations necessary to economically perform industrial assembly. These developments were recently incorporated into a demonstration of programmable automatic assembly of an automotive alternator. The work has been divided into four broad areas: 1) analysis of insertion tasks; 2) task statistics; 3) economic analysis and assembly system configuration choices; and 4) programmable automatic assembly demonstration, with the following results.

Analysis of Insertion Tasks. Round peg-hole insertion tasks with chamfered corners are by far the most frequent in assembly of metal products with machined or cast parts. This task was extensively analyzed and a complete statement of the requirements on relative errors is now available. The important design variables have been identified and for many parts it has been determined that conditions for successful assembly can be met more easily than the clearances between the parts would make it at first appear. These analyses have been amply verified experimentally and it has been shown that the conditions can be obtained from the blue prints for the parts. The analysis and experiments also form a valuable pattern which can be followed in the analysis of other tasks.

The geometry of angular errors in screw thread mating has also been analyzed and shown to have looser error tolerances than typical peg-hole insertion tasks. Cases where the peg touches one side of the hole and both sides of the hole have been considered. Two types of "jamming" during assembly have been identified, and the conditions for preventing them specified in terms of the geometry, the friction coefficient, and the arrangement of the applied forces.

Careful experiments have been carried out with a spring loaded wrist device coupled to a sensitive 6-axis force-torque sensor. This device was attached to a milling machine base and specific relative errors were imposed on insertion tasks using special test pegs and holes. All data were gathered and processed on-line by a computer. The results verified

the conditions derived for one of the two predicted types of jamming and showed that unambiguous force and moment data could be obtained.

The combination of geometric and friction analyses, plus the stimulus of the above data, gave rise to the invention of a totally new device for accomplishing assembly, the remote center compliance. This device accomplishes mechanically what active accommodation does with sensors and servoes and allows chamfered peg-hole insertions with 0.0003 clearance ratio with 1mm (0.04") or larger initial position errors and a few degrees of angular misalignment. The error tolerance of this passive compliance device is much larger than was originally thought possible for passive devices.

Task Statistics. Ten products and subassemblies were examined for two types of characteristics: what assembly tasks occur, and what directions relative to the assembly do the parts approach from. Eight of these products were of cast or machined metal, one of molded plastic and one of a variety of plastic, sheet metal stampings and wires. The latter product was the exception to the findings from the others: 70% of the parts arrive from one direction and 35% of all tasks are single peg-hole insertions. Adding a second direction picks up another 20% of the parts. Screw insertions represent 25% of all tasks, and 10 other tasks make up the rest. This justifies the choice of tasks to analyze, although more extensive surveys could alter the results. It can be concluded that the first 9 products form a group with quantifiable characteristics. In particular, because most parts arrive from one direction, it should be possible to assemble them with devices which have much fewer than 6 degrees of freedom. This has important economic and system configuration ramifications.

A second survey examined industrial design practice with respect to sizes and clearances between parts. Here it was found that particular types of parts, made by certain manufacturing techniques, reliably fall into predictable ranges from 0.001 to 0.01. This confirms the choice of assembly task difficulty to analyze. It categorizes parts by their geometry properties and allows the analytical tools developed to be applied to general manufactured parts.

Economic Analysis and Assembly System Configuration Choices. Economic models have been made of programmable assembly machines and systems of such machines. Simple assumptions have been made concerning machine component costs and cycle times. Comparison models of special purpose assembly machines and manual assembly have been developed from similar assumptions so that relative costs can be obtained. The structure of this model has been examined and conclusions have been drawn concerning the sensitivity of unit assembly costs to various factors. Without an analytical model these vital sensitivity analyses cannot be performed.

Programmable Automatic Assembly Demonstration. The assembly knowledge just discussed was tested on a programmable system. The product assembled is an automobile alternator with 17 parts. The demonstration is performed testing a single computer controlled arm with tool changing capability. This demonstration has yielded much knowledge of a technical and economic nature concerning programmable assembly.

RESEARCH RESULTS SINCE THE SEPTEMBER 1977 REPORT — The specific objectives of the current year's work have been to capitalize upon and to extend recent developments in part mating theory. The earlier work in part mating thoroughly investigated the forces which occur during positive clearance fits of round pins and holes under quasi-static conditions. We have now extended our investigations to negative clearances (interference fits) and to high speed insertions.

The RCC and the 6-axis force sensor have both been subjected to additional theoretical analyses. They have also been reconfigured several times during application engineering for several industrial customers. A new series of experiments on force sensing during assembly is just beginning.

Part Mating Activities. A theoretical investigation of negative clearance (interferences) insertions is now in progress. Its objectives are: 1) to find the insertion force for quasi-static force fits given the dimensions and materials; 2) to determine the parameters necessary for the selection of an appropriate hammer for hammered force-fits; and 3) calculate the forces developed during hammered force fits. Analytical solutions have been developed to describe the insertion force for a peg into a hole for any pair of materials which both obey Hooke's law. The minimum energy for further movement of a hammered force fit or a press fit can now be calculated. Future activities here will include modeling the behavior of pneumatic hammers, developing a model to account for the effects of static preloads and fixture design on hammered force-fits, and extensive experimental testing to verify analytical models.

The investigation of high speed insertions has caused a reexamination of the RCC (discussed below). One of the key questions to be answered here is: during a high speed impact, is the center of percussion of the suspended mass more important than the center of compliance? To date equations have been developed that can predict the motions of the mass suspended in the RCC after impact. The lateral and angular velocities of the suspended mass must be known along with the coefficient of restitution for the materials involved. An equation for an effective mass was also developed for more precise determinations of the coefficient of restitution. These equations were developed by representing the suspended mass as a bipolar equivalnet mass system. An experiment is planned to verify the validity of this action.

The amplitude of the bounces can be reduced by increasing the stiffness (reducing the compliance) of the RCC. However, if the stiffness is sufficiently large, it is possible that the sliding motion during the insertion can be restricted. The three regimes that occur during the sliding part of an insertion are being analyzed so that the maximum stiffness that will allow insertion can be determined. The three regimes are sliding on the chamfer, one point contact sliding and two point contact sliding.

Before the system can be modeled the equations of motion for the various regimes must be developed. In addition to the three previously mentioned regimes, the free vibration situation must be considered. Differential equations have been developed for all but the two point contact situation. During an insertion several changes in the boundary conditions take place. As the insertion passes from one regime to another, changes in the direction and magnitude of the various forces acting on the suspended mass occur. Geometric restrictions also change with depth due to the chamfer. These effects must be accounted for in the model.

Several subtle nonlinearities may also be added to the model. While the migration of the Center of Compliance due to deformation of the RCC has been shown to be insignificant, a change in the magnitude of the latter stiffness due to deformation may be great enough to require modeling.

It is hoped that by varying the inertia and compliance elements of the RCC and suspended mass, a more rapid insertion can be realized. It may also be necessary to add damping to the system to reduce free vibration.

A milling machine is still being used as a testbed for assembly experiments. It has recently had a D.C. motor attached to the pinion which lowers the quill. After this system has been tested over a range of controlled rate insertions, a special high speed insertion station will be built to investigate insertion speeds unobtainable on the mill.

Optimal Chamfers

As part of a large part mating program for an industrial sponsor some results on optimal chamfers have been obtained, of which some can be presented here. The problem is to find the optimal slope for a straight chamfer. Optimal is defined as yielding the smallest work to achieve insertion:

$$\text{Min} \int_{Z_0}^{Z_1} F_I dz$$

where F_I is the Z axis (or insertion direction) force required for insertion, Z_0 is where the part first strikes the chamfer (considered constant) and Z_1 is the bottom of the chamfer. If we assume that the part to be inserted is long compared to its diameter, and it is supported by a rotational compliance at the end far from the inserted portion, then F_I is approximately

$$F_I \cong \frac{K(Z_0-Z)(1+Z^1\mu)}{Z^1-\mu}$$

where Z is the travel distance of the part since striking the chamfer at Z_0, K is the effective lateral support stiffness, Z^1 is the chamfer stops (to be chosen optimally), and μ is the coefficient of friction. Carrying out the minimization results in

$$Z^1 = \mu + \sqrt{\mu^2+1}$$

Some examples are:

μ	Z^1	Chamfer Slope in degrees
0	1	45^o
0	1.618	58^o
1.0	2.414	67.5^o
2.0	4.236	76.7^o

RCC Development. The success of the RCC has led to many inquiries about possible applications. One challenging application was for a press fit done at high speed. It was necessary to recheck the validity of the assumptions behind the design since it was originally designed to do clearance fits at low speeds.

The ideally behaving planar RCC consists, in part, of a four bar linkage with pinned-ends. In its common realization the pinned ends are replaced by elastic wires. The question is whether the effects of this replacement on the kinematic behavior of the RCC are significant under any load condition.

It was decided to ignore the portion of the linkage allowing translation, on the basis that its behavior is acceptable in either embodiment, to establish an elastic multi-element beam-column element computer model of the wires and manipulate the model with various loads, noting deflections and inferring the center of rotation for each set of loads.

The conclusions were that in the geometry range of existing RCC units, the use of elastic links does not have a significant effect on the deformation geometry. The rotational compliance is very stiff to either a lateral or an axial force (at least for force levels small compared with buckling critical forces) and while center of rotation deviates greatly from its ideal location at the focus, under load of such forces, the associated deformations are negligible. Significant deformations occur, of course, in response to an applied moment, but the center of rotation is at or near the focus. Under combined axial lateral forces and an applied moment, the deformation response to the moment swamps that of the forces and the center, and while not at the focus, is very, very close.

The RCC under axial loads was also studied since the spring constants are augmented by the presence of that load. These spring constants are:

$K_X \sim F_V/H_L$ and $K_\theta \sim F_V L(\frac{2L}{H} - 1)$, the second equation is a simplification of:

$$\frac{M}{F_V} = \left[\left(\frac{D}{2}\right)^2 \left(\frac{1}{H} - \frac{1}{L}\right) + L\left(\frac{2L}{H} - 1\right) \right] \theta \ .$$

The variables are defined in Figure 1.

The first RCC units sold to customers were designed to be "bulletproof". While no failures were anticipated, any necessary repairs would have been very difficult. A new design (Figure 2) is now being tested which offers the same function at lower weight and cost (7075 aluminum vs. 17-4PH stainless steel). While it is less well armored, it offers ease and economy of repair. The rate of creation of new designs is also accelerating.

Six-Axis Force Sensor Development. Effort has been applied to the design and development of the six-axis wrist sensor. Motivations include some operational difficulties with the sensors in our own laboratory as well as the experience of the first users.

Development follows completely traditional and straightforward lines. Particular aspects exposed and studied include gate heating, operating temperatures, and excitation; materials, material stress limits, and material specific errors or uncertainties; gage and bridge configurations, compensation, bridge configuration-specific non-linearities and bridge sensitivity; surface preparation, adhesives, and gage backing; amplifier choice, size, location and grounding; sensor geometry and specialization for different magnitudes and mixes of loads. The goals are to be able to produce conservatively-configured sensors for long life stable laboratory/industrial use and to be able to quickly configure and design sensors for specific requirements in a largely routine way.

Data Taking Facilities. A computerized data-taking test station has been developed for the measurement of forces during parts mating experiments. The facilities include a test bed, six degree of freedom force sensor, data acquisition electronics, minicomputer, data-taking software, and hard copy output units.

The test bed is a modified Bridgeport milling machine (see Figure 3) allowing accurate x, y, and z alignments and motions of test parts. The spindel, or z axis of the milling machine, which is the one generally used for mating, is instrumented with a position measuring potentiometer, soon to be replaced with a LVDT. Of the parts to be mated, one is mounted on the bed, and the other attached to the spindle. The six axis force sensor is either attached to the spindle, or mounted on the bed as a pedestal type sensor.

Signals from the force sensor and position transducer are passed through low pass filters, multiplexed, and digitized by a 12-bit analog to digital converter, before being read by a Nova 2 minicomputer. Presently, the computer inputs a complete set of force and position data every ten millseconds. The data acquisition electronics, however, will permit cycle times as short as 0.25 milliseconds.

A software package has also been developed to support data taking experiments. Programs, which are generally interactive, are written in BASIC, with assembly language subroutines to handle interface I/O. Calibration programs automate the process by which the sensor's 36 element calibration matrix is determined. Test programs verify proper sensor performance. Data-taking programs record the forces and z axis position, versus time during experimental matings, while subtracting out preloads and biases, resolving actual forces from raw sensor output voltages, and correcting for geometric offsets. Data, which are stored in core memory during real-time recording, are automatically dumped onto disk files along with documenting information. The disk files are available for future access by programs which post-process the data, generate complete line printer outputs, or automatically plot selected data.

This software package has proven to be very convenient to use. Because it is written in an interpretive rather than compiled language, it can be readily modified to adapt to the needs of a particular experiment. Due to its interactive nature it has been easily used by persons having no programming experience. This has enabled the gathering of an enormous amount of data. The force histories of nearly 10,000 part matings or separations have been recorded, and hundreds of plots have been computer generated.

Presently, though, the milling machine quill must be lowered manually. Work is being done, however, to motorize the quill drive, and provide digital control. Expected benefits are finer position control, smoother velocities, and computer synchronization, resulting in better experimental data.

Force Feedback Experiments. Early work on force feedback and arm control revealed that the processing of force sensor information placed a heavy load on the CPU. At a minimum this processing requires the subtraction of initial offsets from the six element input vector of sensor voltages, and multiplication by a 6 x 6 matrix. Generally, additional matrix operations are required to translate to other coordinate frames. The existing operating system, which ran on a 10 millisecond update cycle, could not handle this additional computation.

Distributed processing was decided upon as the best approach for solving the problem. A Digital Equipment Company LSI-11 was chosen as a satellite processor for preprocessing the sensor output. The LSI-11 has direct control over an A/D converter and multiplexer connected to the sensor via a serial link. Two unidirectional 16-bit buses provide communication between the LSI-11 and the Nova. The Nova is the host computer, downloading the LSI-11 from its own disk, and controlling its operation. The LSI-11 will read the sensor, subtract offsets, and multiply by both calibration and geometric transformation matrices. The results are communicated to the Nova through a simple semaphore protocol.

An alternative approach to the problem of processing force sensor information is to use a dedicated analog device to perform the matrix multiplication which transforms the raw sensor voltages into resolved forces. Such an analog processor has been designed and built. It utilizes operational amplifier summing networks with weighted resistor values to perform the transformation.

The main advantages of this device over a computer approach are cost and size. Materials cost is less than \$200. Measuring only 12 x 8 x 8", it is highly portable, yet contains both power supplies and meter output display. A sensor and analog force processor alone, with no other equipment, can comprise a complete instrumentation system. Other devices such as chart recorders, can be easily interfaced.

The primary disadvantages are accuracy and flexibility. The tolerances of the various components leads to errors on the order of 5%. The calibration matrix is not as readily changed as with a computer. The entire resistor network must be physically replaced when a sensor is changed, or a new geometric offset is desired. A computer can handle these modifications easily and virtually instantaneously.

Furthermore, proper software can compensate for preloads and biases, whereas the analog processor requires the manual zeroing of 6 potentiometers.

Despite these drawbacks the analog force processor has proven to be a useful laboratory research tool. It may also be suitable for specialized industrial applications particularly monitoring procession manual assembly.

An improved version, with digital display, is under construction.

The vertical or z axis of the electric arm differs from the other 3 axes in that it requires a constant motor drive signal just to maintain its position against the force of gravity. If allowed to fall under its own weight it will quickly develop sufficient momentum to cause serious damage to the wrist assembly or work table fixtures. To prevent this an electrical brake is mounted on the axis. The brake is normally locked; electrical power is required to release the brake and free up the z axis. Relay interlocks cause the brake to grip whenever power is removed from the motor servo drivers.

Unfortunately it is possible for a failure to occur downstream from the interlock circuits--a component internal to the motor controller, a circuit breaker, or perhaps a relay contact. Under such circumstances an undetected loss of power to the motor would occur resulting in a crash. Such an accident did, in fact, occur, demonstrating the need for a backup protection circuit for actuating the brake.

The circuit that was developed compares actual and commanded velocities to detect when the axis has a downward velocity that significantly exceeds the command velocity. Such a condition exists when the arm is falling. Unfortunately, it also occurs briefly during starting and stopping motions. A special filtering circuit, however, distinguishes between actual falling and false transient states.

Inputs to the protection circuit are the velocity command input signal to the servo controller, and the tachometer signal from the arm. Output is a relay wired into the same interlock system that actuates the brake and shuts down the arm.

As a further protective step the original brake that was supplied with the arm was replaced. A similar model, but with twice the holding torque was installed in its place. It is hoped that no further schedule-shattering malfunctions will occur.

Pedestal Force Sensor. During the initial alternator assembly experiments a 6-axis force sensor was mounted in the wrist of the manipulator arm. This sensor provided information about insertion forces of various parts (notably the insertion of the bearing into the alternator front housing). It was then determined that mounting the force sensor under the workpiece would supply additional information during assembly. For example, while a wrist-mounted force sensor would indicate the angular displacement of a peg entering a hole, a pedestal force sensor would more readily indicate the lateral displacement of the peg relative to the hole. This information is of use not only in force-feedback assembly but also to speed up the teaching process by allowing the arm to detect errors in positioning.

Several considerations influenced the design of the pedestal force sensor. Rather than fabricate a new type of force sensor, the pedestal was designed to accept the 6-axis force sensor which was previously mounted on the robot arm. The pedestal serves as a mounting point for the force sensor, to which is attached a plate serving as the assembly jig for the alternator subassembly. The pedestal force sensor is able to monitor the forces involved with inserting the bearing in the alternator front housing, and fastening the bearing retainer.

An accident resulting in damage to a force sensor mounted on the robot arm also influenced the design of the pedestal. That is, it must protect the force sensor from a catastrophic impact by the robot arm. This was accomplished by mounting the force sensor and assembly jig within a thick walled aluminum casing, held in place with spring-loaded plungers.

In normal use the assembly jig is supported only by the force sensor which, in turn, is supported within the casing by the spring-plungers. An excessive force on the assembly jig releases the plungers and causes the jig to bottom on a shoulder inside the casing. This transfers the load to the casing, protecting the force sensor. See Figure 4.

This unit is now mounted on the milling machine for the initial experiments. It will soon be transferred to the robot's assembly stage to begin experiments on the value of force feedback during both teaching and automatic operation.

Alternator Assembly Experiment. Several significant results and conclusions were obtained from the alternator assembly experiment.

1) Adaptable, programmable assembly of a real industrial product was accomplished. As of this writing, approximately 75 alternators have been assembled (many by disassembling the same sets of parts). Adaptability was demonstrated by the system's ability to absorb position error of 0.05 in. (1.25 mm) or more, due to part variation, uncertainty of part location in feeders, softness of feeder mounting, and lack of precise assembly fixture alignment. Programmability was demonstrated by our ability to program different assembly sequences using substitute tools when other tools were broken, to improve the program's reliability by teaching it "tricks", and to shorten the cycle time by a combination of new tools and more efficient teaching. The basic software system is sufficient to support programs and assembly sequences for a wide variety of products containing similar assembly tasks.

2) The performance of the system was thoroughly documented. A detailed time study was made. From an industrial point of view, the major missing element is inspection during assembly. Improvements to the software system would be necessary to support inspection, but the basic software structure is sufficient. The system's strong point was its reliability in performing the insertions themselves. Its weak point was in performing tool changes. The tool rack's gripper mechanism should be redesigned. There were occasional problems picking up one part (the rotor) and from time to time the screw feeder failed to feed a screw.

   It was determined that the system as constructed could assembly an alternator in 2:42. Working with documented time-motion studies, we found that the system had the potential for assembling an alternator in 65 seconds if many alternators were made at once, with tool change time spread over all. This short cycle time also required some tooling improvements and a design change. No change in software or arm performance was assumed. Further reductions are possible. See Figures 5, 6, 7, 8, and 9.

   Alternators are needed in large quantities. It is not clear whether duplicates of the system tried here would be an appropriate way to meet the demand for alternators. A progressive line might be better.

3) A detailed cost analysis was made. Among other things, we found that feeders cost about $1,000 per part fed and tools cost about $1,000 per part handled. The figures are for low-speed feeders and assume experienced engineering and design personnel at usual industry pay scales. The figures are also biased by the particular tool designs and by the fact that we took pains to design tools for multiple purposes.

4) The concept of engineered compliance was shown to be sufficient to perform a variety of difficult single-direction tasks vertically. The impact of the RCC on system design style, design and debugging time, and ultimate performance was profound. Rather than estimate a time needed for debugging insertion tasks without the RCC, we prefer to state that some tasks could not have been reliably and repeatedly performed at all without it.

5) The software and teaching techniques appear adequate. The 4-axis arm design makes visualization of the geometric relationships by shop floor personnel easy. It thus appears feasible to divide the programming as we have done: an industrial engineer lays out the feeders and tools and writes the flow sequence in the high-level language; a shop floor teacher (or in the future a CAD/CAM data file) inputs the arm position data corresponding to this program. The advantages of this technique are its hands-on immediacy, its simplicity, ease of debugging, and relatively simple software. Potential weaknesses could emerge if extensive reteaching were to be needed in a great hurry. Note, however, that the original program to assemble the alternator contained 141 lines and about 200 points. It was written in 3 hours and the data taught in 2 additional hours. This should be compared with design time of 4 months and debug time of 3 months, plus over 12 months to create the software system. (Each of these projects had the equivalent of about 1.5 men for the time stated.) The alternator assembly experiment has been documented in a sound color film.

Technology Transfer to Industry. Part of this year's work has been to transfer to industry the technological developments in the science of parts mating. One form of this transfer has occurred within the Draper Laboratory in the area of precision component assembly (gyroscopes and accelerometers). For reliable performance these components have very precise surface finish and very tight tolerances. All components of this family of instruments are assembly by highly skilled craftsmen under strict clean room conditions. As higher performance for these instruments is demanded, tighter tolerances and clearances will be needed to meet these needs. As economic pressures mount to produce less expensive instruments, there is greater need to develop a reliable assembly process.

A program was carried out with Internal Research and Development funds to adapt the techniques for parts mating to the assembly of gyro reaction wheels. The wheel analyzed had a bearing assembly that was inserted into its bore to form a shrink fit assembly. To reduce the time between the tests to be conducted, an actual bearing package assembly and a dummy wheel were constructed for a clearance fit at room temperature. This clearance (600 μ in. or C=.0007) was the same that would be expected when performing this shrink fit assembly with actual flight hardware with the correct temperature gradient.

The equipment consisted of a high sensitivity force sensor, a compliance designed for previous parts mating work and the piece parts that are being assembled. A systematic input of lateral and angular misalignments were set up and the insertion forces required for these errors were recorded. From this data a specific force sensor and compliance were designed for clean room use. Figure 10 is a typical data plot obtained from these series of tests that were conducted.

Following the completion of the initial testing program, a specific compliance and force sensor were designed for specific loads to be encountered. Figure 11 shows two compliances (one in its protecting housing). A manual inserter station was designed and constructed to facilitate the assembly of these components in a clean room environment. An analog force processor, described elsewhere, in conjunction with the insertion device, completes the instrumented insertion station for precision component assembly (see Figure 12). This station can thus be used to obtain force data on precision component assemblies.[1] As of this writing, test pieces are being manufactured to perform the actual shrink fit assemblies of gyro reaction wheels under clean room conditions. With this new application of science of parts mating to precision component assembly, the reliability of these components will increase with a decrease in the production cost.

Several RCCs have been sold to industrial customers (see Figure 13). One, shown in Figure 14, was part of an experimental assembly station which pressed a small brass insert into a hole in an aluminum casting. Neither the location of the hole nor its direction were tightly controlled. However, this proved to be not a problem with the RCC. We are working with another industry which is trying to make the RCC spring from rubber and thus add to its standard product line. Another customer has duplicated our milling machine insertion test stand. So far, 6 RCC units and 2 force sensors have been sold. There are several other orders pending.

[1]The Z-force data is also sent to a comparator which can appl brake before the force can get high enough to harm the assembly.

PROGRAM OBJECTIVES — The program objective is to exploit the knowledge base developed to date. This includes the systematic procedures for analyzing part mating tasks, part mating knowledge, experimental equipment and procedures, and the design experience for generating RCCs for different applications. New devices currently being tested should be of interest for the non-chamfered insertion task, such as hydraulic valves. The application of the analytical techniques to a host of industrial tasks is of paramount importance if technology transfer is to succeed. The analytical techniques include a study of the geometry of parts, determination of the force and friction interaction between parts as they slide together, and the combination of these to produce criterion for the design of assembly tools or fixtures and prediction of how to avoid jamming of parts.

The supporting experimental equipment is a necessary part of this transfer, otherwise the necessary verification before try out on a manufacturing floor could be hazardous.

To accomplish this transfer many techniques are being explored. A number of them are reported here and others are in the planning stage.

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6) Production Engineering, 25, No. 5, "Production Research--Path to the Promised Land", May 1978.

Film

1) A 10 minute, 16mm, optical-sound-track, color film, "Computer-Controlled Assembly" illustrating the alternator robot assembly and discussing parts mating research. Copies are for sale at $75 each from: C. S. Draper Laboratory, Inc., M.S. 65, 555 Technology Square, Cambridge, MA 02139. It is available on loan within the U.S.A.

Videotape

1) A 58 minute color videotape describing the latest Draper Laboratory research results in industrial assembly has been produced under another NSF grant. This tape is called "Computer Controlled Assembly", serial No. 50-204, and is available from: MIT, Center for Advanced Engineering Education, 105 Massachusetts Avenue, Cambridge, MA 02139 (Room 9-223). It is available for purchase at $395, or a 5-day rental at $59.

2) A 20 minute black and white tape (AV No. 278) describing and illustrating Force Sensor Calibration has been made and is available for sale at $30/copy from: C. S. Draper Laboratory, Inc., M.S. 65E, 555 Technology Square, Cambridge, MA 02139.

Note: Both tapes are recorded on 3/4 inch U-Matic format.

Papers

1) Kondoleon, A. S., "Results of Programmable Assembly Machine Configuration Studies", presented at Robots II, Autofact I, Cobo Hall, Detroit, MI on 3 November 1977.

2) Drake, S. H., Watson, P. C., and Simunovic, S. N., "High Speed Robot Assembly of Precision Parts Using Compliance Instead of Sensory Feedback", a paper peresented at the 7th International Symposium on Industrial Robots, October 19-21, 1977, Tokyo, Japan.

3) Nevins, J. L., Whiteney, D. E., et al., "Assembly Research and Manipulation", a paper presented at the 1977 I.E.E.E. Conference on Decision and Control, December 7-9, 1977, New Orleans, Louisiana.

4) Nevins, J. L., Whitney, D. E., and Seltzer, D. J., "Research Issues for Automatic Assembly", a paper presented at the 15th Numerical Control Society Annual Meeting and Technical Conference, April 9-12, 1978, McCormick Inn, Chicago, and published in the conference's proceedings.

Distributions

Approximately 350 copies of "Exploratory Research in Industrial Modular Assembly, Fifth Report", C. S. Draper Laboratory Report No. R-1111 (September 1977) have been sent throughout the world.

Approximately 25 copies of the film "Computer Controlled Assembly" have been sold in the Unites States and abroad.

During the past year there have been over 40 separate visits of 118 people to the C. S. Draper Laboratory to discuss the possible application of this research to various problems.

Seminars

1) Nevins, J. L., "State of the Art of Automated Assembly", lecture given at the Automation Montage, sponsored by the Technological Institute of Copenhagen, June 7, 1977, Copenhagen, Denmark.

2) Whitney, D. E., "Draper Laboratory Assembly Research", lectures given in support of the MIT Industrial Liaison Office and the summer course in Artificial Intelligence.

3) C. S. Draper Laboratory staff, "Part Mating Theory". A series of lectures given to various industrial sponsors interested in applying this knowledge to their product design.

CONTACTS — The following contacts are all located at the following address and telephone:

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	J. F. Padavano (S. B. Candidate)
	C. C. Selvage (S. M. Candidate)

DELIVERABLES — The deliverables fall into three categories, namely: 1) devices, such as the RCC, 6-axis sensor, and the special tooling developed; 2) design tools, such as techniques for designing RCCs, geometric analysis for studying or redesigning pieces or products, task analysis techniques for classifying assembly tasks and determining requirements on assembly systems, and economic modeling for comparing various assembly methods, product assembly configuration studies and sensitivity analyses for determining the principal cost items of assembly configuration requiring research activity; and 3) assembly software, a five level hierarchical system for real time control of product assembly has been constructed that is capable of being extended to multiple arms and many kinds of sensor devices.

The technology transfer of these items to industry, as described earlier, is actively being pursued through the mechanism of research agreements. Under research agreements specific applications serve as a focus for transferring the developed knowledge.

During the past year six Remote Center Compliance (RCC) units hsave been sold and delivered and six more are on order and under construction. Additionally, two 6-axis force sensors have been sold and delivered.

Patents. We have been advised that the patent office has allowed the patent application of the RCC and 6-axis free sensor and that receipt of the respective patents is expected within a few weeks. The specific patent applications are the Remote Center Compliance by Paul C. Watson, No. 4098001, and the 6-axis Force Sensor by Paul C. Watson and Samuel H. Drake, No. 4094192.

An invention disclosure for a refined RCC has been made by Samuel H. Drake and Sergio N. Simunovic.

COLLABORATORS — The following comprises a list of industries participating in the program.

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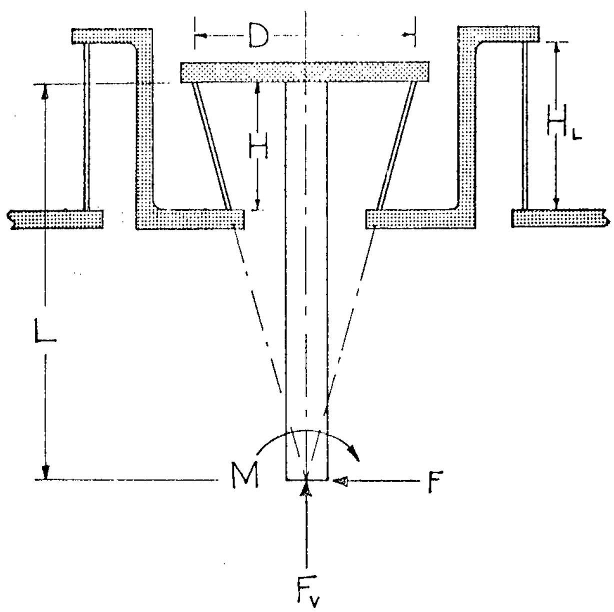


FIGURE 1. SCHEMATIC OF RCC FOR STIFFNESS ANALYSIS

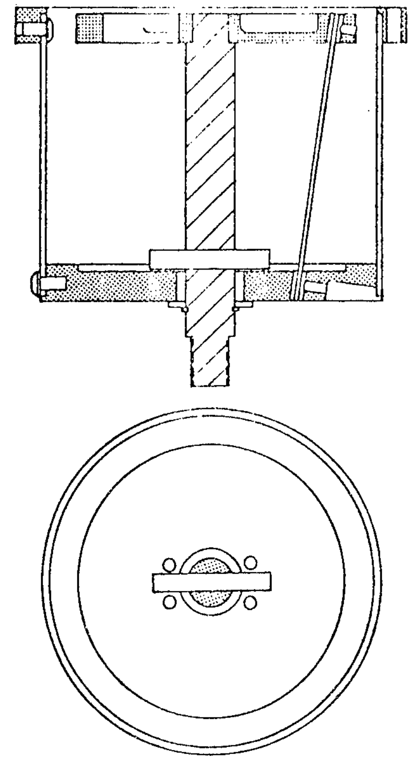


FIGURE 2. MODEL 4B REMOTE CENTER COMPLIANCE

Designed to provide a lighter weight (1 lb. or .45 kg mass) unit capable of easier repair and lower cost. The focal length and elastic parameters are nominally the same as the Model 4A.

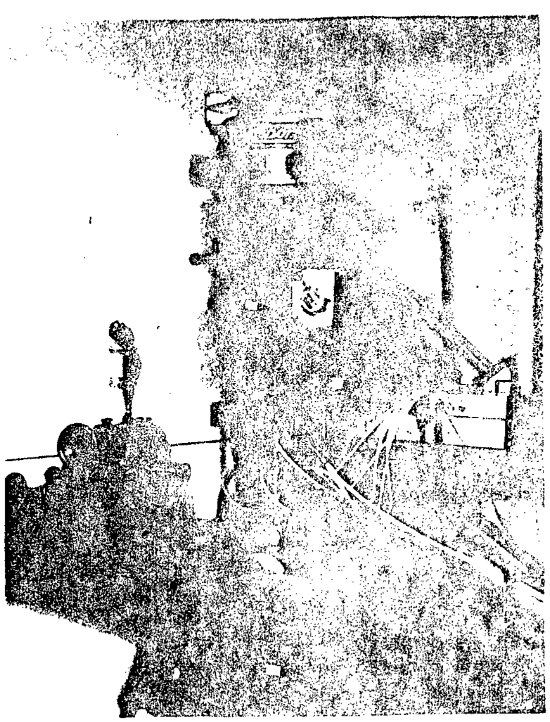


FIGURE 3. DRAPER LABORATORY PARTS-MATING EXPERIMENTAL TEST STAND

The spindle and table of the vertical mill may be fitted with a variety of tooling, measuring or control hardware. Quantitative data on mating forces and moments can be displayed, read into a digital data file or plotted. As shown, the spindle is fitted with an RCC and 6 degree-of-freedom aluminum force sensor. The nominal maximum forces and moments of the aluminum force sensor are:

Axially

400N (100 lbs)	Force
20 Nm (200 in lbs)	Moment

Laterally

200 N (50 lbs)	Force
10 Nm (100 in lbs)	Moment

Resolution of one part in 2,000 of the maximum axial force is possible.

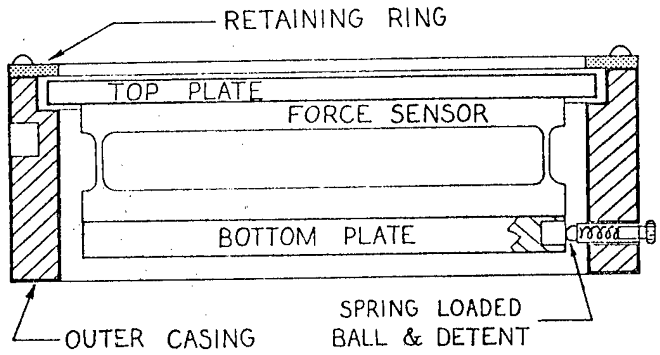


FIGURE 4. PEDESTAL FORCE SENSOR

Unit is protected from static overload forces by a break-away mounting. The break-away mounting is adjustable for static force as torque level. Once broken away, forces are transmitted to the outer casing directly by the fixture plate.

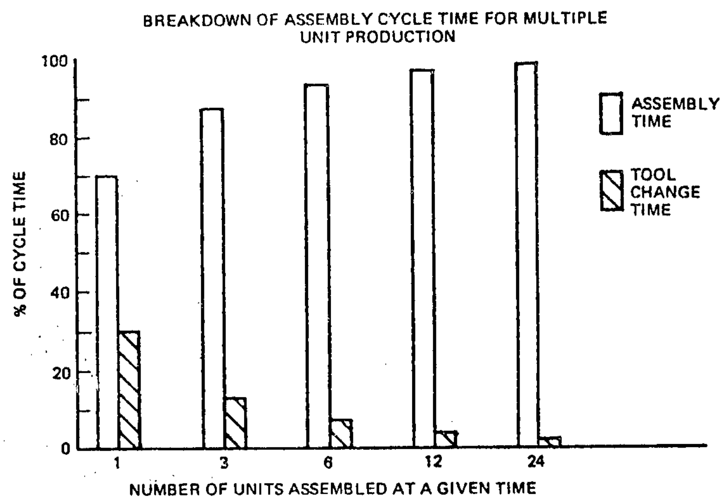


FIGURE 5. Reducing effect of tool change by building several alternators at once.

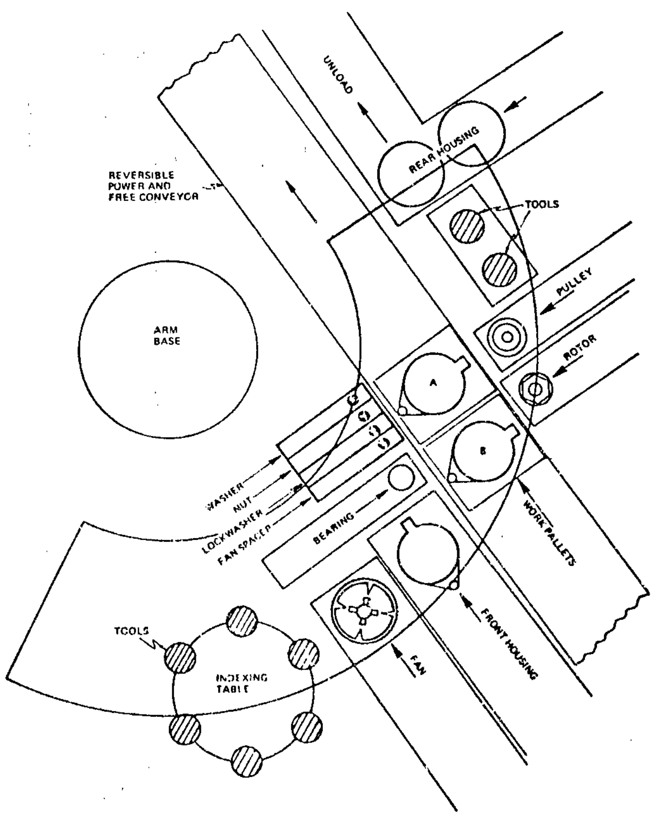
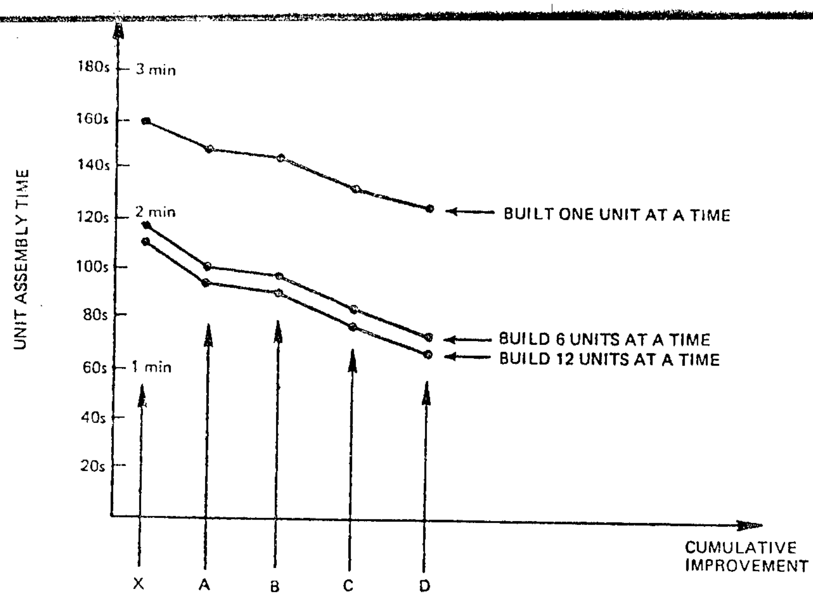
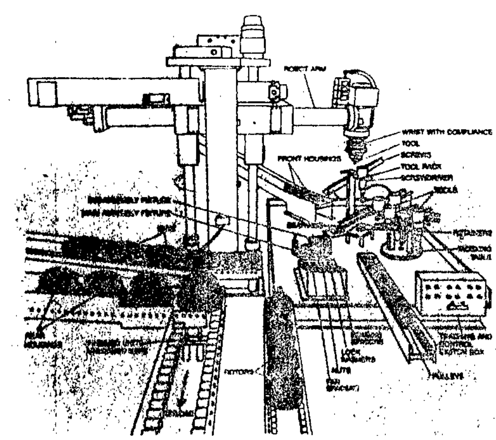


FIGURE 6. Possible Assembly Station layout for building several alternators at once.



X: PRESENT LAB SYSTEM
A: DRIVE 3 SCREWS AT ONCE WITH A 3-HEAD SCREWDRIVER
B: DESIGN CHANGE TO ELIMINATE BEARING RETAINER PLATE, PLUS A.
C: PICK UP ROTOR AND TIGHTEN ROTOR NUT WITH ONE TOOL INSTEAD OF TWO, PLUS A AND B
D: ELIMINATE SUBASSEMBLY STATION AND BUILD ENTIRE ASSEMBLY ON ONE FIXTURE, PLUS A, B AND C

FIGURE 7. Effect on time to build one alternator of various improvements in tooling and product design.



FIGURES 8 AND 9.

Layout of the Robot Assembly Station places tools and parts within easy reach of the Robot's arm, which has four degrees-of-freedom. The assembly task requires six different kinds of tools, held on a table that "indexes," or turns, to supply the proper tool for each operation. The alternator's 17 parts are fed by gravity from 12 feeders. (The 17 parts include 3 screws, which have only one feeder, and 3 long bolts, fed together with the rear housing.) The assembly is performed on two different fixtures, one for the main assembly, the other for a subassembly. The Robot is operated by a computer that drives the four points to designated stopping at designated speeds. The points, speeds and tool operations are programmed with the aid of a control box and a simple keyboard language. The language names and sequences the points and tool operation. A major feature of the Robot is a wrist-and-gripper mechanism that responds compliantly so that parts can be inserted into close fitting openings without jamming.

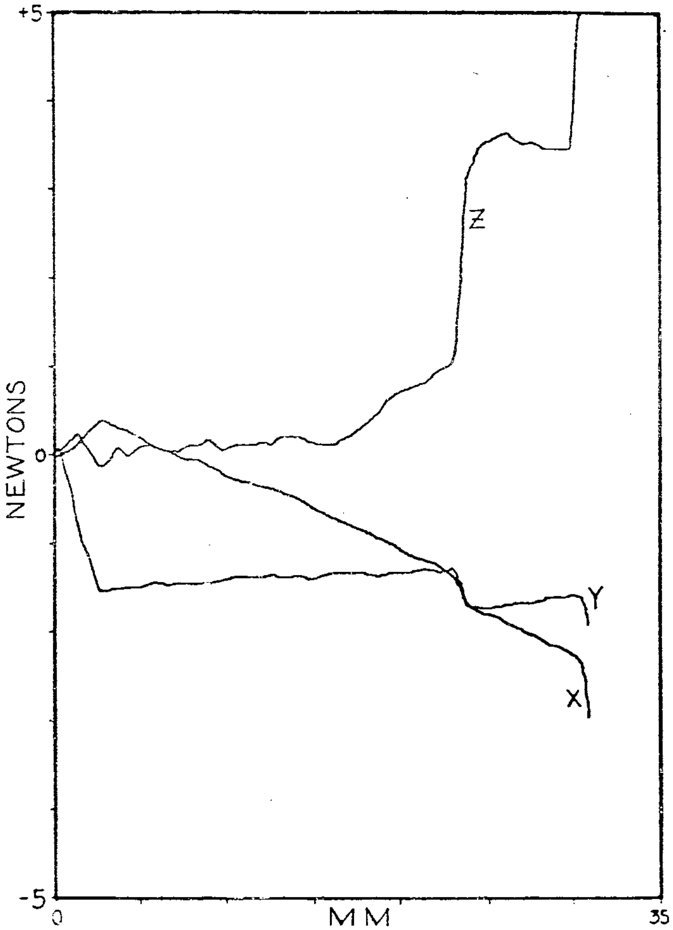


FIGURE 10.

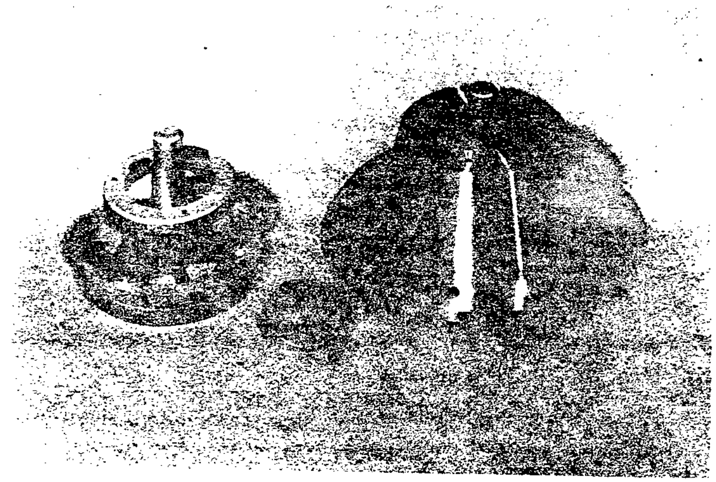


FIGURE 11. SMALL RCC

A small RCC designed for the manual instrument bearing installation stand. Its manual specifications are:

Focal Length From Base	12.5 cm	(5 in.)
Lateral Stiffness	185 N/cm	(100 lb/in.)
Torsional Stiffness	0.12 Nm/mrad	(1.2 in lb/mrad)

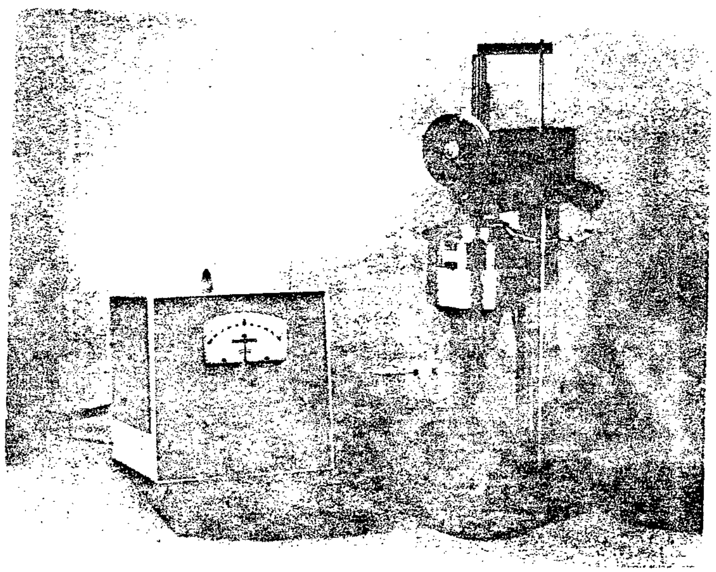


FIGURE 12. FIXTURE FOR AIDING RAPID, REPRODUCIBLE MANUAL INSTRUMENT BEARING ASSEMBLY.

Instrument ball bearings are a light interference fit at operating temperatures and are assembled into a heated housing to provide assembly clearance. The assembly must be done quickly and at light force levels. It is common in unaided assembly that a ball bearing will jam and have to be driven home. A manual assembly stand assisted by the RCC to avoid jamming, and a six degree-of-freedom force sensor to document the assembly force history, is expected to yield significant improvements in the process. A brake is included in the design; activated by the force sensor, it can retard the drive and limit the seating forces exerted on the bearing. Any one of the six forces and moments measured may be selected for analog display (on the meter to the left of the assembly stand). Each or all of the measured quantities may be stored on a computer file or recorded for permanent record.

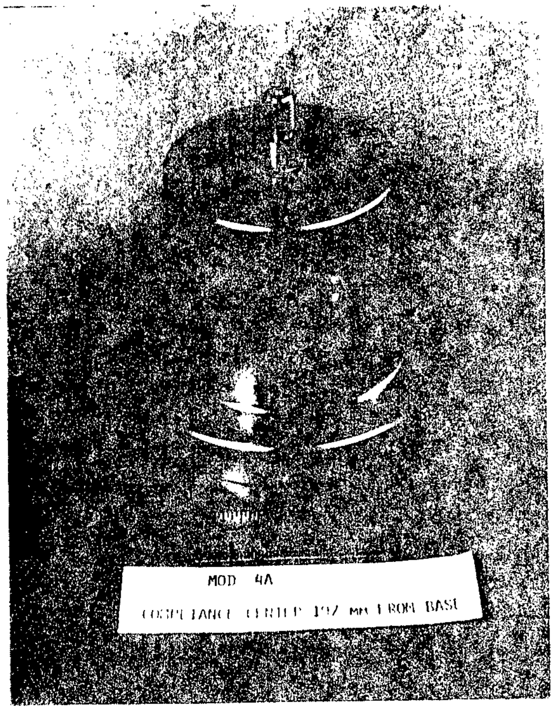


FIGURE 13. MODEL 4A REMOTE COMPLIANCE CENTER

The 4A RCC has been designed as a rugged and relatively foolproof unit with overload protection in all directions. It was designed to provide a unit for evaluation by industry in the industrial environment. Several models of the 4A have been placed in industry. Its nominal specifications are:

Mass (weight)	1.36 kg	(3 lbs)
Focal length from base	20 cm	(8 in.)
Lateral Stiffness	100 N/cm	(55 lb/in)
Torsional Stiffness	0.1 Nm/mrad	(0.9 inlb/mrad)

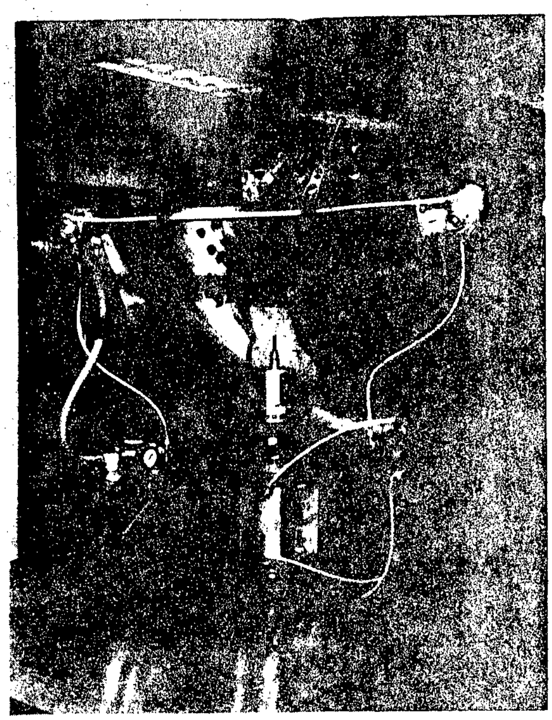


FIGURE 14. ASSEMBLY FIXTURE INCORPORATING RCC

An assembly fixture incorporating the RCC for the purpose of centering and erecting a small brass ferrule to be driven into an interference hole in an aluminum casting. The purpose is to avoid possible problems with jamming and subsequent broaching by using the unique properties of the RCC.

MACHINE INTELLIGENCE RESEARCH APPLIED TO INDUSTRIAL AUTOMATION

Reported by David Nitzan
September 1978

Work performed by the Industrial Automation Group
SRI International

PROGRAM OBJECTIVES - It is essential to advance automation in batch manufacturing of discrete products for both economic and social reasons. Our nation is faced with economic needs to combat inflation and to compete effectively in world markets. We should also improve the working life of the labor force and raise the standard of living of the population as a whole. To fulfill these requirements we must develop a new technology, called "programmable industrial automation," whose salient characteristics are flexibility and adaptability -- the capability of a machine system to perform a variety of tasks under variable conditions -- and ease of training -- the efficient facility with which factory personnel can program the system to perform these tasks. Programmable automation systems existing today include industrial robots that are flexible and easy to train for jobs performed under fixed conditions, but these robots are not adaptable. They are unable to replace human workers who use their muscles, senses, and brains to perform material handling, inspection, and assembly tasks under variable conditions. To overcome this limitation, we should develop intelligent robots, consisting of arms with versatile end-effectors, sensors, and computer control.

The main objectives of our program are to (1) develop general-purpose and cost-effective hardware/software techniques for computer control of modular systems of manipulators, sensors, and other components that are flexible, adaptable, and easily trained for performing material-handling, inspection, and assembly tasks, and (2) transfer this technology to industry.

Our mode of solution consists of (1) developing basic techniques and hardware/software modular subsystems for manipulator path control, machine vision, sensor-controlled manipulation, accommodation, training aids, and distributed microcomputer communication; (2) integrating these subsystems into a programmable system and experimentally demonstrating training and execution of material-handling, inspection, and assembly tasks; (3) affiliating with industrial companies that provide us with practical, production-related automation problems, assess our solutions, and absorb the technology we develop through mutual visits, consultations, transfer of hardware/software modules, quarterly progress-report meetings, and publications.

PROGRAM ACHIEVEMENT - Major accomplishments from April 1973 through September 1977 include those described below.

A. Techniques and Hardware/Software Modular Subsystems - We have developed techniques and modular systems of hardware and software (source code in the BLISS-11 language) in the following areas.

Manipulator Path control - We have developed analytical techniques and a library of software subroutines to control the trajectory of a manipulator, including (1) transformations between Cartesian and joint coordinates of a Unimate arm; (2) transformations between different Cartesian coordinate frames, such as frames attached to the Unimate base, its end-effector, a work station, a moving conveyor, and a workpiece; (3) smooth path control for arbitrary trajectories.

Machine Vision - To sense the image of a stationary object, we have used a solid-state TV camera (General Electric 100 x 100-element Model Z7891 or 128 x 128-element Model TN-2200); to sense the image of a moving object, we have used either a TV camera with a flash-lamp strobe or a linear-diode array. The gray-level data acquired from the image sensor are converted into binary (black and white) to reduce the amount of image data, thereby increasing the speed and reliability of processing and lowering the cost of equipment. We have developed analytical techniques and a library of software subroutines for many vision functions, including (1) finding "blobs" (connected regions) and extracting a set of distinguishing features of each blob "on the fly"; (2) training the vision subsystem to recognize an object on the basis of a subset of these features by simply showing the object to the TV camera in different orientations; (3) determining the identity, position, and orientation of objects that are either stationary or on a moving line.

Sensor-Controlled Manipulation - We have developed hardware and software techniques for using sensory feedback to control the motion or action of the end-effector of a manipulator, including (1) binary signals (e.g., from a contact sensor) to stop or start the motion or action of the manipulator end-effector; (2) a calibrated vision subsystem to determine the identity, position, and orientation of an object and to control the manipulator motion relative to that object by dead reckoning; (3) visual servoing, using an "eye in the hand" (a GE 100 x 100-element solid-state TV camera mounted on the Unimate end-effector) to reach an object target by measuring and correcting the displacement error between the target and the end-effector camera until that error is sufficiently small.

Accommodation - We have designed and built a triaxial, pneumatic accommodation device, which is mounted between the wrist and end-effector of a manipulator. Equipped with position and force sensors, this device can exert on the workpiece a controllable force along each axis, such as zero force (for passive accommodation), positive or negative constant force, and force proportional to the end-effector displacement (a programmable "spring"). We have also incorporated passive accommodation into an x-y table by letting its top float freely on a ball slide within a given tolerance; alternatively, the top can be rigidly locked to the table's frame.

Training Aids - Using the Cartesian-to-joint coordinate transformations, we have developed analog and digital joysticks to manually control end-effector motion in Cartesian room coordinates. Using a commercial phrase recognizer (Threshold Technology VIP-100), we have also controlled the Unimate motion by voice commands. We have developed, and continue to improve, a user language to facilitate the writing and debugging of application programs for a variety of tasks employing the Unimate.

B. Experimental Task Demonstrations - We have integrated the techniques and hardware/software modular subsystems described above and applied them to laboratory demonstrations of different tasks, including the ones described below.

Material-Handling Tasks: (1) Part Recognition - Using the training-by-showing capability, the vision subsystem was trained to recognize 4 casting types in 7 different stable states and 8 different parts of a water pump. (2) Acquisition of Moving Parts - Different parts (connecting rods, water pumps, etc.) were placed randomly on a moving conveyor belt. As each part passed under the camera, the identity, position, and orientation of that part were determined by the vision subsystem. Based on this information, the Unimate was commanded to track the part, pick it up, and transport it to its destination. (3) Packing Water Pumps in Box - Using feedback from a proximity sensor and a triaxial force sensor in its end-effector, the Unimate acquired individual water pumps from approximately known positions and packed them neatly in a tote-box. (4) Packing Moving Boxes - Boxes were placed randomly on a moving conveyor belt, the vision subsystem determined the position and orientation of each box, and the Unimate packed castings into the box regardless of the conveyor speed. (5) Bin Picking - We have built an end-effector with four electromagnets and a contact sensor to pick up four separate castings from the top of a pile of jumbled castings in a bin. The Unimate transported the four castings and set them apart on a backlighted table. The vision subsystem then determined the stable state, position, and orientation of each casting. With this information, the Unimate gripper acquired each casting and, depending on its stable state, transported the casting to its destination. (6) Stenciling Moving Boxes - Boxes were placed randomly on a moving conveyor belt and the vision subsystem determined the position and orientation of each box. Using this information, the Unimate placed a stencil on the upper right corner of each box, sprayed the stencil with ink, and removed the stencil.

Visual Inspection: (1) Water Pumps - Washing-machine water pumps were inspected to verify that the handle of each pump was present and to determine which of two possible positions it was in. (2) Lamp Bases - A group of lamp bases was inspected to verify that each base had two electrical-contact grommets and that these grommets were properly located.

Assembly: (1) Pop Riveting - Force sensing was applied to detect a hole and trigger a one-sided riveting in that hole. A pneumatic Chobert riveting gun was mounted on a leaf spring on which a strain gage had been cemented. A search algorithm was executed by the Unimate until the riveting gun mandrel entered a hole, causing the leaf spring to deflect; this deflection was sensed by the strain gage, the pop riveting gun was triggered, and the mandrel was pulled to expand the rivet in the hole. (2) Insertion of a Retaining Ring - Attached to the Unimate wrist, the triaxial accommodation device was used to insert a retaining ring in a slot on a cylindrical shaft with a 4-mil tolerance, making use of both constant applied force and passive accommodation. (3) Bolting of Compressor Head - We applied visual servoing to the job of bolting a compressor head to its housing by eight bolts. The bolter (a pneumatic wrench) and the GE 100 x 100- element TV camera were mounted on the z component of the triaxial accommodation device. Calibration was done manually using a trial-and-error procedure and the coordinate-transformation software. The bolting operation consisted of performing 3 servo repetitions to find a hole and move the Unimate accordingly, inserting a bolt into the hole, and tightening the bolt.

RESEARCH RESULTS SINCE THE SEPTEMBER 1977 REPORT - Progress has been achieved in the following areas.

A. Vision Module - We have designed and constructed a practical visual sensing module for development and execution of application programs entailing vision tasks. These tasks include training-by-showing for part recognition; determination of the identity, position, and orientation of parts, holes, and the like; and visual inspection of the integrity of parts and assemblies. The Vision Module consists of three major components (see Figure 1): A GE Model TN-2200 solid-state TV camera with 128 x 128 elements; a DEC LSI-11 microcomputer with a 28K-word memory; and an interface preprocessor between the TV camera and the microcomputer. The microcomputer memory stores the entire vision library previously developed at SRI, as well as some application programs and newly developed capabilities. These capabilities include the ability to specify a "window" in the image and to compute the area and first and second moments of each blob within the window faster than by invoking the connectivity analysis of these blobs.

The interface preprocessor performs five functions: (1) providing an adjustable threshold for converting the analog intensity data to binary image data; (2) buffering the binary image data of one frame (128 x 128 bits) to permit the LSI-11 to read in the image data later at a rate independent of the camera speed; (3) converting the binary image data into run-length code, i.e., the image coordinates of the transitions from black to white and white to black (this general purpose feature may save up to 25% of the processing time in the LSI-11 microcomputer); (4) providing a second adjustable threshold that, together with the first one, can be used to generate intensity histograms (we intend to analyze these histograms and apply them to automatic adjustment of the first binary threshold); (5) triggering a flash lamp in synchronism with the frame scan of the TV camera.

B. Visual Servoing - We have built a small projector to illuminate a scene with a planar bar of light for visual servoing. The image sensed by the TV camera is a bright streak that depends on the three-

dimensional line of intersection between the light plane and surfaces in the scene. For example, occlusion results in discontinuity in the streak itself, whereas a step change in the surface normal results in discontinuity in the streak's direction. In this way we can sense three-dimensional objects whose reflectance is identical with that of their background.

We have developed software to detect nonhorizontal streaks in images and fit straight-line segments to these streaks. Each segment is then characterized in a fashion similar to the one we use to characterize a blob in the image. We have mounted a TV camera and the light-bar projector on the wrist of the Unimate arm. Using our new line-finding subroutines, we are able to perform visual servoing in three dimensions. We are experimenting with this configuration to simulate spot welding on a moving line and to follow lines, grooves, and corners on stationary objects. We have found that the response of the overall servo system is limited by the mechanical components of the Unimate rather than by the PDP-11/40 processing time.

C. Assembly Using Visual Feedback and Passive Accommodation - We have been exploring innovative configurations and techniques for cost-effective flexible and adaptable assembly with minimum jigging. The first version of such an assembly process has been demonstrated and we are now working on the second version. In both versions a compressor cover is fastened to its housing by 8 bolts.

The assembly station in the first version (see Figure 2) consists of the following components: (1) a Unimate arm under direct control of an LSI-11 microcomputer, constrained to move between 8 fixed positions, thereby simulating a less costly 4-joint limited sequence arm with servoed wrist rotation; (2) a gripper, mounted with a linear potentiometer on a pneumatic-cylinder piston to provide force control and displacement sensing along the vertical direction; (3) a programmable x-y table whose frame is driven by two dc servomotors (with 5-mil accuracy) and whose top is either rigidly attached to the frame or free to move relative to it (within +/- 6.3 mm in either x or y direction) to allow passive accommodation; (4) a GE Model Z7891 solid-state TV camera with 100 x 100 elements above the x-y table; (5) auxiliary items, consisting of a pneumatic bolter (impact wrench) held by the Unimate gripper, a bolt feeder, and two fixtures -- one for the bolter and the other for the compressor cover; (6) a DEC PDP-11/40 minicomputer, which supervises the the Unimate LSI-11 microcomputer and controls the remaining components of the system.

Following a one-time calibration procedure establishing the parameters of transformation between the image coordinates of the TV camera and the axes of the x-y table, the compressor housing is placed randomly on the x-y table and the assembly operation proceeds as follows. The TV camera takes a picture of the compressor housing and the minicomputer analyzes its image, computes its position and orientation, and commands the x-y table to move the housing to a fixed arm-stacking position at the center of the camera's field of view. The Unimate then picks up the cover and places it on the compressor housing while the x-y table is freed to passively accommodate any minor cover misalignment. The minicomputer analyzes the cover image seen by the TV camera, computes the position of the first bolt hole, and commands the x-y table, with its top rigidly locked, to move and align the bolt hole at the central stacking position. The Unimate acquires the bolter, picks up the first bolt, and inserts it in the cover hole. As the x-y table is now freed to passively accommodate any minor bolt misalignment, the Unimate drives the bolt into the housing by spinning the bolter and exerting a constant vertical force downward, and then moves away. Performing in-process inspection, the minicomputer analyzes the cover image seen by the TV camera and verifies that the hole image has disappeared (if not, a second trial is executed before aborting the operation). The last three steps are repeated for the remaining 7 bolts, after which the Unimate returns the bolter to its fixture.

In the second version of the assembly, the following improvements are being introduced: (1) The bolting operation is performed by a pneumatic 4-joint limited sequence arm, the Auto-Place Series 50, whose rotary joint is driven by a dc servomotor and whose end-effector is a bolter; (2) the Vision Module (described above) is used as a self-contained vision subsystem to sense and process visual images in response to top-level commands from the supervisory PDP-11/40 minicomputer; (3) the Unimate is being used to present parts with the aid of visual feedback in lieu of jigging, namely, picking up the compressor housing from a moving conveyor belt and picking up the cover from a tote-box containing semiorderly packed covers.

D. Communication in Distributed Processing - We have been developing a distributed computer system consisting of a PDP-11/40 minicomputer and LSI-11 microcomputers (see Figure 3), each performing an isolated modular function, such as controlling a manipulator and its end-effector and nonvisual sensors; visual sensing and processing; controlling auxiliary equipment (x-y table, part presenter, etc.) and its nonvisual sensors; safety monitoring; and voice control. Since most tasks are controlled by more than one microcomputer, we have developed a system of hardware and software for intercomputer communication. The communication hardware consists of 16-bit parallel input-output interface units (DR11-C interface in the PDP-11/40 and DRV-11 interface in the LSI-11). The communication software is organized hierarchically so that a user can invoke any of the high-level functions provided without being required to know either the details of the communication protocol or that some functions are being executed remotely. This software organization protects programs in one computer from the effects of changes made in another computer and simplifies programming for new jobs.

Our current distributed system consists of a supervisory PDP-11/40 mini-computer and two LSI-11 microcomputers, one controlling the Unimate and its end-effector and the other constituting part of the Vision Module.

E. Robot Programming Language (RPL) - We have completed and are now applying the first version of an interpreted, FORTRAN-like user language, called RPL, to facilitate the writing and debugging of application programs on a PDP-11/40 minicomputer for material-handling, inspection, and assembly tasks. Application-program statements consist of calls to executable library subroutines (which may take arguments) or to interpretable, user-defined RPL subroutines (which at present do not take arguments). The current library includes subroutines for the following functions: controlling the Unimate arm and its end-effector; defining and computing position/orientation transformation matrices; visual sensing and processing to recognize, locate, and inspect objects; opening and closing equipment relays; teletype input/output; arithmetic, trigonometric, and vector functions; and branching.

The RPL software includes a compiler and an interpreter, both written in the BLISS-11 language, which currently run under DEC's RSX-11/M operating system. The compiler reads the user-program text from a disk file, translates it in a single pass into an interpretable object code, and writes that object code on a disk file or a cassette. After being loaded and started, the interpreter first reads the interpretable object code from the disk file or the cassette into memory and then begins to call library subroutines with appropriate arguments according to the instructions in the object code. Although executable RPL object code would run faster than interpretable RPL object code, the increase in speed would not be significant because the computer usually spends most of its time executing library subroutines and relatively little time interpreting the RPL object code. On the other hand, the use of an interpreter permits the user to debug his application program easily and efficiently. Nevertheless, for certain tasks (e.g., high-speed visual inspection), the user may wish to rewrite a debugged RPL application program in FORTRAN, compile it, and run the entire executable object code faster.

RPL programs now run in the distributed-processing system described in Section D above. The maximum size of an RPL application program is currently about 125 steps; this size will be increased by using a smaller operating system (DEC's RT-11), devising a dynamic overlay structure, or both. RPL could be improved by adding the following features: arguments to user-defined subroutines; arithmetic and logical expressions; assignment statements; function subroutines; subscripted variables; local variables; condition monitors; and dynamic memory for some variables.

F. Part Presentation for Assembly - We have designed and constructed a programmable unit for presenting different three-dimensional parts, which are too large to be handled by a bowl feeder, to an assembly station. The unit employs a vibratory chute, a Vision Module, and an Auto-Place arm--all under minicomputer control. As shown in Figure 4, the unit consists of three circular compartments and, above these, a circular "shuttle" that can push individual parts from one compartment to another. The floor of the first compartment, called an "elevator", can move down to a programmable level and then back up to the base level. The backlighted translucent floor of the second compartment, called "turntable", can rotate to a programmable orientation. The third compartment is simply a container for rejected parts. The vibratory chute is mounted above the elevator, and the TV camera of the Vision Module is mounted above the turntable.

Using the RPL user language, an application program was developed for the part-presentation operation. As the first step in this sequence, the vibratory chute is energized until a part falls onto the elevator while the shuttle is above it, whereupon this fall is sensed by a microswitch and the vibratory power is turned off. The shuttle moves the part to the center of the turntable, where the stable state and orientation of the part are determined by the Vision Module. If the part is wrong, it is pushed by the shuttle to the reject container. If the part is right but in the wrong state, then the turntable rotates the part to the proper orientation, the elevator is lowered to a level corresponding to that state, and the shuttle pushes the part into the elevator and drops it to the correct state; the elevator then rises to the base level and the shuttle moves the part back to the center of the turntable. The Vision Module determines the orientation of the part and the turntable rotates it into a fixed pick-up orientation. The Auto-Place arm now swings in, picks up the part, and transports it to its destination in the assembly station.

PROGRAM OBJECTIVES FOR NEXT PERIOD - We plan to concentrate our efforts on the following problem areas.

A. Visual Inspection - We will use our existing hardware/software vision system and develop new methods, algorithms, subroutines, and applications programs for visual inspection of the integrity of parts and subassemblies. We will use structured light to obtain the 3-dimensional information and to enhance the image contrast of three-dimensional objects. we will also add attributes of the relationships among holes and other object components to the set of distinguishing features.

B. Visual Servoing - We intend to analyze the whole servo system, which incorporates the line-following visual feedback and the Unimate arm, and improve its performance (stability, smoothness, speed, and accuracy.)

C. Vision Module - We will improve our existing Vision Module by adding new features, such as the displaying and processing of image data within a specified window; allowing sequential operation of up to four TV cameras; having two image-data buffers for motion analysis from one viewpoint or for stationary analysis from two viewpoints; and summation of pixels to shorten the software processing time.

D. Part Handling - We will apply visual feedback to improved or new methods for presenting unoriented parts to assembly stations, packing unoriented parts in containers, and picking jumbled parts from bins.

E. Robot Programming language (RPL) - We may improve RPL by adding certain capabilities that are important and relatively easy to implement, such as arguments to user-defined subroutines, arithmetic and logical expressions, and assignment statements.

F. Automatic Assembly Planning - We will study the incorporation of a software supervisory layer above RPL to be able to perform automatic planning of a new assembly task, or modify an old one, by generating the appropriate RPL application program. This study will be based on Artificial Intelligence planning techniques using networks of action hierarchies and world modeling.

G. Assembly - We will continue our efforts to develop cost-effective techniques for flexible and adaptable assembly with sensor-controlled manipulation, in-process inspection, and minimum jigging. The development areas described above will be integrated into such an assembly system.

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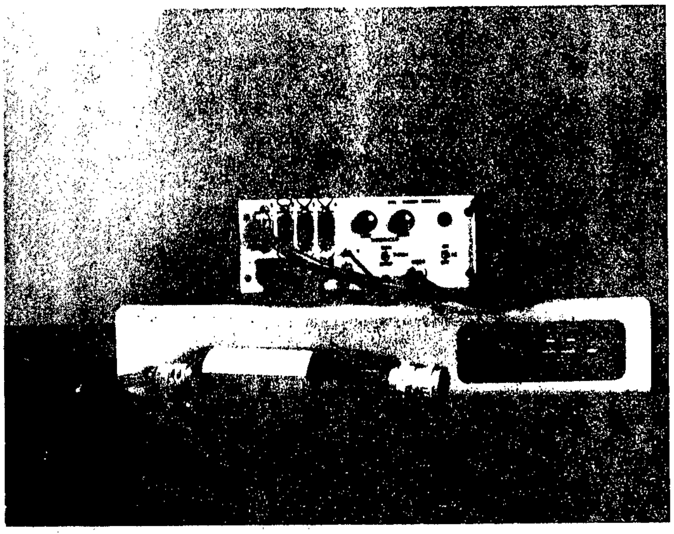

FIGURE 1 VISION MODULE

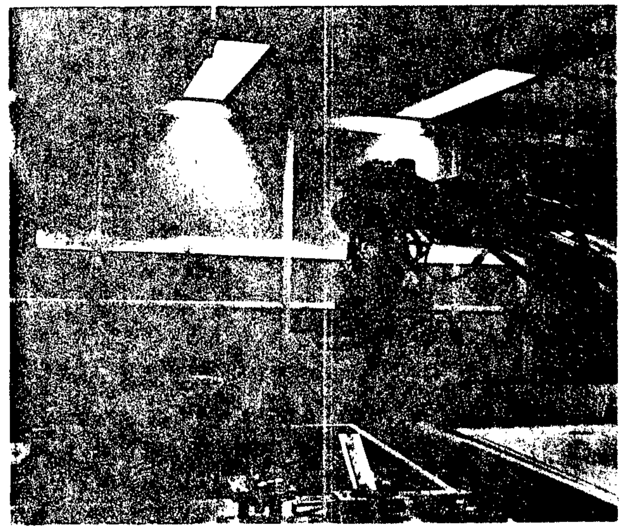

FIGURE 2 ASSEMBLY STATION

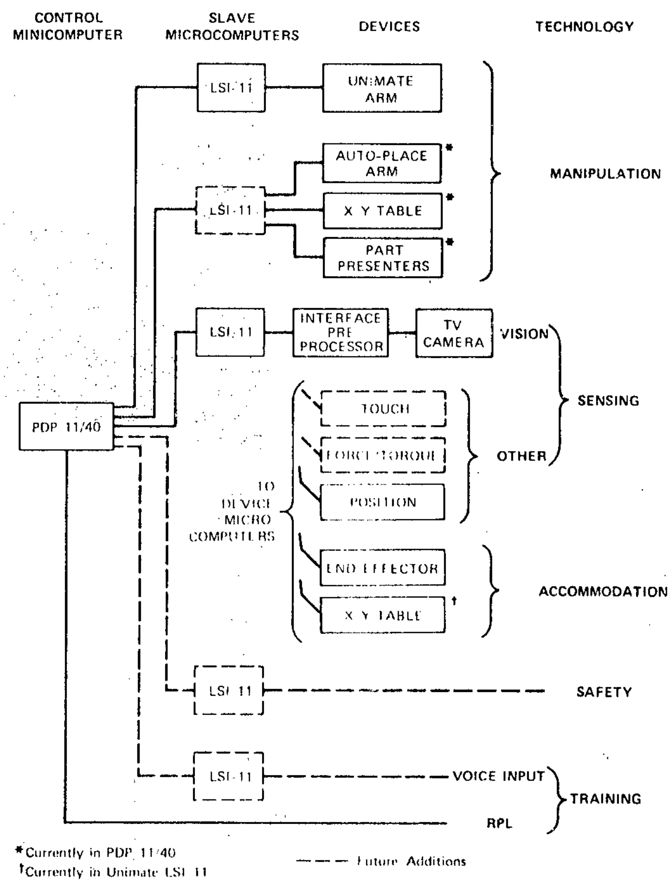

FIGURE 3 DISTRIBUTED COMPUTER SYSTEM

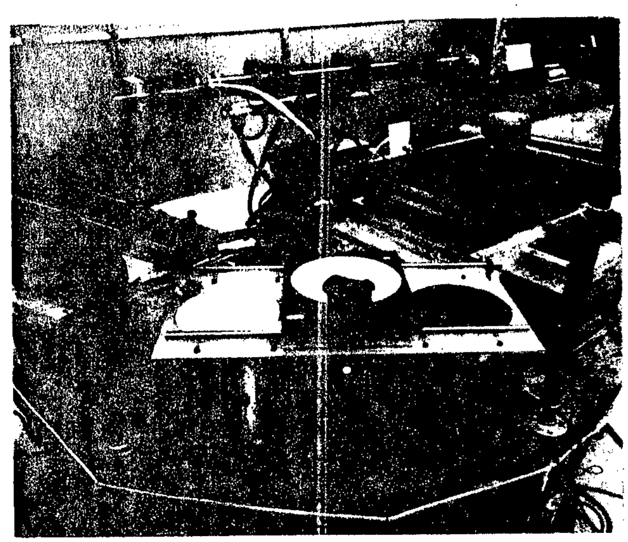

FIGURE 4 PART PRESENTATION FOR ASSEMBLY

Computer Integrated Assembly Systems

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Program Objective - The objective of this research is to solve fundamental problems which stand in the way of building practical programmable systems for discrete parts production. It is intended to demonstrate technology with which programmable systems can do more tasks, be more cost-effective, and be simpler to set up and program than current systems. Research is directed toward three capabilities: 1. Very High Level Language for programmable devices; 2. sensory/motor control; 3. inspection and vision. Results of this research apply across a broad range of programmable production systems from industrial robots for medium volume and batch production to relatively special purpose automation for high production volumes.

The research has been integrated in the AL system. AL is intended to serve for programmable assembly as APT did for numerically-controlled machining. The research deals with three problems of productivity: difficulty of adequate inspection; low productivity in medium volume and batch production; and the difficulty of automating hazardous tasks.

There are two directions visible in research in productivity technology. One is to minimize manipulator hardware cost by using minimal degrees of freedom and special purpose hardware. This is important for the short term. Our approach is based on the estimate that even if manipulators and computers were free, system costs would decrease only about a third. In typical systems, engineering costs dominate. But computers with high performance will have low cost in the near future. Sensing and vision will likewise become inexpensive. There is good reason to believe that low cost robots will become available. If low cost computers, vision, sensors, and robots are available in the near future, how can they be used in tradeoffs to cut overall system cost? This research concentrates on software to make effective use of them.

The following capabilities can cut the amount of engineering and setup cost: self-calibration and self-setup; advanced software capabilities based on models; standard vision and sensing modules which are powerful enough to work without special case preparation and programming. Production can be increased by getting into production more quickly, moving more quickly up the learning curve and maintaining higher reliability. These benefits require continuous monitoring capabilities and integration with the production system to feedback results of inspection into production control, and continuous self-calibration for reliability.

PROGRAM ACHIEVEMENT 1974-77 - The project built up a coherent program of software, hardware and experimentation which led to the first computer integrated assembly system in 1973. The assembly system was used to assemble an automobile water pump from 10 component parts [1,2]. The assembly included using a power tool and several fixtures. Force and touch sensing were used extensively, and vision was used in several places in the assembly. The current NSF program was begun after the water pump assembly. Subsequently the system was extended to use two manipulators in performing assembly of a hinge [3]. The assembly system was used to perform the piston-crank and clutch sub-assemblies of a two-stroke gasoline engine [3]. Those assemblies were performed to demonstrate the use of sensing for automating setup and alignment of assemblies.

Paul built our first software system for assembly, WAVE [4]. It was the first system to provide several important features for assembly: automatic transformation between joint angles and Cartesian space; a predictive dynamic arm model with joint inertia and gravity used in software servo (the improved arm model allows higher performance for the manipulator), automatic planning of smooth trajectories, modification of planned trajectories in response to variations in locations of parts at runtime; rudimentary force and touch sensing used in control; and a macro library of assembly operations which made successive assembly tasks increasingly quick to program [1].

Design requirements for a manipulator had been formulated on the basis of previous software and hardware experience. During 1970, Scheinman designed and built a manipulator to these design criteria [5]. A second arm was built and operating in 1974. Scheinman designed a second model, the MIT arm, based on the Stanford arm. A total of about twenty of the two models of the manipulator have been installed in research laboratories around the country. The arm is having a major impact in industry. Unimation is now building an industrial manipulator based on the Scheinman arm.

The AL System

After completion of the water pump assembly, several assembly experiments were performed to gain experience in programming assemblies and to test the integration of sensing in setup and assembly. A system redesign was undertaken [6] to provide for: multiple assembly devices in synchronized, concurrent and cooperative operation; capabilities for moving assembly lines, especially arithmetic transformations of position and orientation; more general trajectories; higher level constructs such as specifying motion of objects rather than motion of the manipulator. In AL [6], the user can specify

MOVE bolt TO hole.

The system automatically keeps track of locations of parts of a subassembly when the subassembly is moved. This direction has also been taken in the AUTOPASS project by the automated assembly group at IBM.

The AL system has been in operation in complete form for a year. Finkel, Shimano, Taylor, Goldman and others have developed it to the point that it is an easy task to compile and run an AL program. It is a system for users, not just for its builders. Numerous people have come in with no previous experience with AL and gotten programs working in a short time.

The AL system includes an advanced system for teaching-by-guiding. It provides the added capability to model an assembly; if the assembly fixture is moved or rotated, the assembly operation can be reprogrammed by changing two fiducials. M. Gini and G. Gini designed and implemented a new version of the POINTY system [12] originated by Grossman and implemented by Taylor. The new version is simpler to use than the old; it accepts a subset of AL necessary to build AL models. POINTY uses the arm as an input device and outputs a file of AL declarations containing the model of frames and affixments.

Representation and Modeling

An important part of the AL design is the use of models of workpiece and workstation. They are intended to be obtained from various sources: from CAD information; from POINTY; from vision and sensing; and from symbolic constraints. There are important applications for which simple teaching-by-guiding is inadequate because no operation is repeated and no two parts are identical. Instead, off-line programming from a CAD data base is essential. Parts such as elements of an aircraft wing are very similar yet not identical, and there are CAD models for them. The modeling of parts for assembly was carried out in two systems. Originally, a system based on polyhedral models, GEOMED, was used [10]. Then the SPI system based on our representational scheme, generalized cones, was implemented [11].

Taylor wrote a geometry system in the planning system [14] to translate symbolic constraints of the form "part is against fixture" into a system of inequalities and equalities. Sets of contraints were linearized, and by linear programming techniques, the constraints were resolved to assign positions to parts in the planning phase. The greatest utility of the constraint system was in automatic determination of positional inaccuracies in assembly.

Modeling dynamics of Devices

Ishida designed several new algorithms for cooperative control of two manipulators [21,24]. Cooperative motion appears to be important for handling large or heavy objects, and in many assemblies. The analysis distinguishes translations and rotations as primitives. Complex motions are made from simultaneous two-arm translations and rotations.

Two analyses of manipulator dynamics were performed with the goal of faster response without increasing hardware cost [13,15]. The first was a discrete sampled data system analysis of the manipulator control system. Several conclusions came from this work. The sampling rate could in fact be decreased. The torque equation could be changed to minimize sensitivity to changes in inertia. The equations could be modified to minimize their dependence on the sampling time interval. The more sophisticated state space analysis made little improvement over classical analysis.

Macrosystem Models

Analysis and modeling of assembly were begun. Grossman [16] began a line of investigation of the effects of errors and tolerancing in parts manufacturing and assembly. He used a geometric modeling program to simulate discrete parts tolerancing, to study the propagation of manufacturing errors affecting the probability of successful assembly. A comprehensive Monte Carlo method systematically analyzes stochastic errors. Mujtaba analyzed automatic assembly of a pencil sharpener using the Stanford Arm and compared motion times with MTM (Methods Time Measurement) standards for a human [13]. The task was also analyzed using assembly primitives developed at Draper Lab. For this task, human assembly was much faster.

Glaser and Liu conducted analyses of assemblies of a carburetor, a distributor, a fuel pump, and a generator. Two observations were made: 1. If a screwdriver is provided, 93% of operations are one degree of freedom. 2. An appreciable number of operations involve two manipulators, where the second is used as programmable and controllable tooling; typically, few degrees of freedom are necessary.

Vision

Bolles designed and implemented a Verification Vision system for inspection and visual control of assembly [9]. He interfaced Verification Vision with the AL system [9,23]. Fifteen or twenty tasks were performed with this system. The average time to program a task was one hour. Teaching someone to use the system required about two hours. Parts models are also important for inspection in the Verification Vision system [9]. The SPI system was used to predict curves for the curve-matching process in the Verification Vision system.

Force Sensing

Scheinman built a wrist force sensor with overload protection in 1974. Shimano calibrated it and measured its sensitivity at about 1/2 ounce force, which is close to its designed sensitivity [17]. Shimano and Paul [18] analyzed force control and designed a system based on an approximation to cut computation time to affordable limits. Shimano implemented these ideas in a force control package in the AL runtime system [21]. The system provides motions for which position is controlled by external forces (insertions and parts mating) and motions for exerting forces.

Collision Avoidance

Widdoes [20] made a collision avoidance program for the first three joints of the arm which was a significant improvement over Pieper's earlier program [19]. Both programs could be useful at compile time, but both were too slow for runtime collision avoidance.

RESULTS SINCE THE SEPTEMBER 1977 REPORT

The force sensing wrist is now in operation. Prior to the last grantees' conference, Scheinman rebuilt the Blue Stanford arm with extra wires to accomodate the force sensor; he mounted the Scheinman force sensing wrist and provided an interface board. It uses 8 pairs of strain gages whose outputs are transformed by software to 3 force and 3 torque values. Since the last report, Salamin interfaced the sensor to the PDP-11. Salisbury debugged the software and calibrated the wrist. It has several useful features which are important for our work with small arms and small scale parts and assemblies. It is small, about the size of a stack of four silver dollars. It is light, and sensitive. It measures the weight of a 300 gm mass to about 5 gms standard deviation. Much of the effort came in making the interface in a small package appropriate to the arm, in interfacing so as to measure 8 low level signals to high accuracy, and modifying the arm to accomodate extra signals.

There are certain problems in using any wrist sensor: it provides force and torque information only for single contact; corrections must be made for dynamic effects of the mass of the hand when the arm is in motion (acceleration). The dynamic effects are large and no corrections are yet being made for them. The interface for the wrist sensor can be used for force sensing fingers which were developed by Mujtaba. Force sensing fingers help to deal with both problems; there is little mass beyond the sensors to introduce dynamic effects, and the sensors provide independent information with much higher sensitivity than the wrist, properties which are relevant in tool using and grasping.

Salisbury and Mujtaba made an automatic self-calibration procedure for the wrist sensor in POINTY. This makes calibration quick and simple, requiring no expertise. AL has been modified to use the sensor. The AL expression WRIST(A) returns 3 forces and 3 torques in the array A; the statement SET_BASE establishes zero force and torque levels for current values of sensor readings. Typically the wrist is read within some procedure which is called about 20 times a second. It is expected that another statement, SET_FRAME(T) will be used to specify transformation of force measurements to the coordinate frame specified by the TRANS T. These facilities make good use of additions to AL, namely arrays and procedures. The force control system [21] has been added to AL. It is now possible to have the arm apply or sense specified forces and moments. To avoid incompatible requests the force components must always be orthogonal. To insure this, a force frame must be specified, and the directions of the applied forces and moments must be aligned with one of the cardinal axes of this current force coordinate system. Also specified is whether the orientation of the axes changes as the hand moves, i.e. is the force frame defined relative to the hand or the table (world) coordinate system. An example follows:

WITH FORCE = <sval> ALONG <axis-vector> OF <frame>

This is only a beginning in Very High Level Language for sensory/motor control. Several small introductory programs have been written. One called CG finds the center of gravity of a long bar. Another maintains a controlled force or compliance about a single axis. Another uses force to locate the baseplate in an assembly.

Goldman has extended the AL system in several ways: 1. extensive documentation was produced, the AL User's Manual; 2. programming language constructs were added most of which were not in the original specification: procedures, arrays, CASE statements, new arithmetic and logical operations, user input/output routines; 3. force specifications described above; 4. changes to the graph structure used in the modeling system; 5. separate data and instruction spaces in the PDP11 to make use of additional memory now available. Mujtaba has extended the POINTY system for advanced teaching-by-guiding to execute a large subset of AL and approach the status of an AL interpreter. Some new facilities are: 1. nearly full AL arithmetic capabilities; 2. execution of series of statements from a file; 3. macros (implemented by Pagello) and limited procedures; 4. multi-segment motion statements; 5. the beginnings of a library for assembly. We expect to merge these two parts of the AL system not far downstream into an interactive system running on a stand-alone PDP11.

Mujtaba has completed a film showing the use of POINTY; the film is available for distribution. A set of programs has been written to test new capabilities and to serve as examples of AL programs for pedagogical purposes. They include: 1. VALVE: assembly of a water valve; 2. valve assembly with reprogramming the assembly by determining the assembly position using touch, force, or vision; 3. DECIDE: a decision program which handles castings and rejects those with wrong weights; 4. PUSH: a program which demonstrates various modes of the Shimano compliance system; 5. CG: finds the center of gravity of a long rod; 6. WRISTCALIB: POINTY macro which calibrates the wrist force sensor automatically; 7. POINTY macros which write the alphabet. A set of film sequences of these examples are being assembled.

To aid in assembly experiments, Mujtaba and Salisbury designed and arranged for fabrication of a flexible fixturing system. It was designed to make it quick and easy to set up and reposition assemblies in a reproducible way. A base plate was made with an accurate grid of both tapped holes for clamping and drilled holes for locating pins, combined with a set of clamps and plates to carry individual assemblies. The flexible fixturing cost was minor. The capability to perform experiments in force control and assembly is severely limited by the quality of hardware and control. Effort has been made to improve the arm hardware. Salisbury replaced several harmonic drives of the blue arm, which improved its performance significantly. It is still relatively rough. He has replaced the wiring harness on the Gold arm, the first Scheinman arm. Additional work is required to make it operational again. We hope to replace the two arms with two of an appropriate industrial robot.

A second Workshop on Software for Assembly was held at the Stanford AI Lab, November 29-30. The morning of the first day was devoted to a tutorial of AL and POINTY, the afternoon was spent in hands-on programming with AL and POINTY. The second day was devoted to discussion. Evaluations were solicited about the experience of programming with AL and comparison with other programming systems with which attendees had experimented.

Haas has nearly completed a stereo version of the Verification Vision system. Stereo provides a direct, accurate, and powerful technique for inspection and visual control. Difficulties remain with the monocular calibration of the cameras. When these difficulties are overcome, a stereo self-calibration of cameras and arms will be implemented.

Brooks and Binford have begun a substantial new effort, based on "reasoning about geometry". Brooks is constructing a set of rules for grasping of objects and mating of objects, to operate in a backward-chaining reasoning system. The reasoning system uses object models in the generalized cone representation [25]. A powerful object modeling system is operating and being developed further. This system is the basis for off-line programming of operations using a CAD data base, stereo vision, or interactive graphics modeling. The same system is being used for model-based inspection and vision. The aim is to reduce programming to specifying object models. A natural common language for the system and human operators is based on object models. The system was designed with a high level modeling language.

Objects are modeled in a high level language based on a generalized cone representation of primitives in a part/whole graph [25]. The representations of most objects are very compact; they are segmented into volume parts which seem natural to the user. This modeling system provides graphic aids for the user for modeling generic objects and relations. The representation also seems natural for machine reasoning because important relationships between surfaces are simply represented in the generalized cone models.

The high level modeling system is a byproduct of providing symbolic relations for reasoning about shape. Previous modeling systems do not provide symbolic results which are necessary for reasoning about manipulation and inspection and they are not general enough. They can be classified as those based on a few primitives such as cylinders and blocks [26,27] and those based on polyhedra [10]. Those based on simple primitives were not general enough to represent the objects that were considered. Those based on polyhedra do not have explicit relationships between faces nor do they have the part/whole decomposition needed for reasoning about the models. Previous systems were aimed at hidden surface graphics; in this system, symbolic information about edges and surfaces was needed for reasoning, symbolic information which was not available in those systems. A previous modeling system based on generalized cones [11] provided a background for the design of the new system.

PROGRAM OBJECTIVES FOR THE NEXT TEN MONTHS -

Research will be pursued in the areas of sensory/motor control, inspection and vision, and the AL system.

AL and POINTY wiill be merged into an interactive programming system running on the PDP11. A library for assembly will be begun. The system for reasoning about geometry will be used for a new version of the planning system for AL.

The model-based system and stereo vision will be used for inspection and visual control of assembly. The stereo Verification Vision System will be completed and self-calibration performed for arms and cameras.

Analysis and experimentation with the force wrist will be continued. Analysis and software for closed loop control of a single axis will be carried out as a preliminary to a multi-link study. The computation requirements for sensory/motor control will be evaluated and ways of limiting computation and providing the necessary computation power will be studied. Kinematic studies of design for controlled exertion of force will be carried out, and evaluations made of redundant manipulator designs.

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DESIGN AND CONTROL OF ADAPTABLE - PROGRAMMABLE ASSEMBLY SYSTEMS

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I. GENERAL - Work has just begun on a two year study of the systems aspects of adaptable-programmable assembly systems. Previous work at Draper and elsewhere has shown the feasibility of programmable robot assembly. Most of such work has utilized one workstation with one or two robots. The new work will investigate the system problems of designing and operating multi-station programmable assembly systems. The work will be divided into three main areas:

1. Requirements - what are the characteristics of parts and products that influence assembly system design and how can these characteristics be systematized?

2. Systems - what are the options for workstations and transport layouts and what special control problems do these present?

3. Operational behavior - how do different types of programmable assembly systems behave in the face of different batch sizes, mix of products and assembly requirements, and breakdowns?

Programmable assembly systems seem to have many analogies in flexible machining systems. Both:

- are geared to a mix of incoming work
- aim at below mass production on any one type of work
- have several workstations of undetermined specialization
- exhibit queuing and scheduling problems due to work mix, tool changing, transport saturation, breakdowns, and so on

There are also many differences. Assembly systems:

- may require less precision in construction and operation
- exhibit shorter work cycle times
- require part feeding
- employ tools which may be more generalizable (useful for more operations)
- interface to the rest of the factory in a different way.

A central core of the proposed work will be to explore these similarities and differences further. Contact with other FMS research groups (at Draper, MIT, Purdue, and Europe) will be established and their tools utilized to the extent possible.

The three work areas will now be discussed in greater detail.

II. REQUIREMENTS - Our previous work on assembly requirements consisted of a survey of ten product items which were assembled and disassembled. Many similarities emerged from these seemingly different items, and we found that several characteristics of them were important to the design of assembly systems. For example: pertinent to individual parts: size, weight, clearances, chamfers, support, dimensional stability, insertion distance, insertion type, arrival direction axis, and kinematics. Our work in part mating theory contributed to our ability to evaluate some of these characteristics.

This work needs to be expanded in two directions. First, an attempt must be made to extend this kind of survey to entire product units, to determine the ranges of variables like batch size, model mix, the real differences between models, the flow rate, and the need, if any, for multi-product mix in one assembly system. The procedure will be to work with our industrial partners (AMP,Ford and General Electric), selecting several families of products for study. Care will be taken to ensure a broad sample but detailed study will be given only to a few lines, one or two of which will be retained for study in subsequent tasks.

Second, deeper examination of the parts and assembly tasks in products is needed. Prior work identified insertions of round pegs the most frequent task and found that many products have one dominant insertion direction. While this pattern may not hold up as the sample is broadened, we hope that some identifiable classes of products and tasks emerge. It may be that defining tasks in the human way (insert, twist,etc) is too loose and will never converge to a finite set. A new way of identifying assembly tasks and new designators for tasks may be necessary.

It is hoped that the methods of Group Technology will be applicable. In the long term one can visualize a code to describe a product so that the overall requirements for an assembly can be read from the code. Product families capable of being assembled by the same system could be identified by similarity of the codes, as is presently done in metal cutting.

III. SYSTEMS - We have built and operated a single station programmable seembly system. At present it can assemble a 17 part automotive alternator in 2 minutes 42 seconds using 6 tools and 8 tool changes. In principle it can assemble products about one foot cube in size requiring insertion motions vertically down, or (with appropriate tools) horizontally, or vertically down with some spin about the vertical axis. Electric motors, some types of pumps and gearboxes, electric entrance boxes and terminal board arrays are examples.

The requirements on work stations in an assembly system depend on the presenting tasks in the products to be assembled an on overall production requirements. These will come from the survey data discussed above. A major option for station design is the degree of specialization (as to tasks or task types it can per- orm, number and/or direction of the degrees of freedom, range of motion, number of tools available, and so on). These options will be explored only deeply enough to relate them adequately to requirements data and simple performance models. No station design will be undertaken.

The requirements on system transport facilities depend on both the products and the stations. If stations are specialized, much transport and congestion can be expected, but station operation will be efficient. Many FMS's are designed this way. But FMS station times are long, so the analogy may break down. For assembly, we need to know if there are any generic transport layouts, whether layout detail can be decoupled from system performance, and what should be transported (partially completed assemblies, parts, fixtures, tools, complete parts kits for one unit, pallets full of identical parts, etc). Again, we will explore the options deeply enough to be able to make simple models of behavior, based on parameterized equations.

The result of these efforts will be performance descriptions capable of being analyzed and/or simulated. This work constitutes the last portion of the work.

IV. OPERATIONAL BEHAVIOR - Our experience operating the assembly station in our laboratory showed that tool change time was a dominant feature of its behavior. There is little we can learn from it, however, concerning behavior of systems of such stations. Mathematical analysis and simulation are the tools available.

Any such system presents scheduling (in what sequence should work be introduced) and queuing (do lines form at some stations) problems. Ideally scheduling problems can be eliminated if the work on the system provides equal load for all stations, even if each item on the system presents unequal station loads. The eqqual load criterion is so powerful that it is important to study its consequences. For example, if stations can do some of each others' work, (due both to adequate station/tool design and prescient product design) then the load can be redistributed to achieve balance. But random fluctuations in station time, inevitable if sensory feedback is used, plus other fluctuations, will upset the neat balance. Do such upsets spread to other stations? Does steady state operation occur and how large must batches be for this to happen? Noting that such questions have been investigated for FMS, where the station times are long relative to transport and tool change times, do recent findings carry over to programmable assembly? Or are there critical relations between station time, transport time, amount of inprocess inventory, pallet and tool change time, and output rate?

These questions will be looked at in several ways. Existing mathematical tools (such as Purdue's CAN-Q) will be expanded as necessary to model the critical events in an assembly system. Extremes of system type (lines, islands, loops) will be analyzed, using simple example layouts. Stochastic simulations of these same layouts will be made to determine other operating behavior to compare to CAN-Q. When the product surveys have progressed sufficiently, one or two specific examples will be chosen for detailed representation, the objective being to provide depth and avoid incorrect generalizations.

V. WORK PLAN - 1. In conjunction with industrial affiliates, select for study a number of product lines which appear from previous work to be possible candidates for programmable assembly: manufactured in mix or batch mode with low to mid volume production requirements. Disassemble and reassemble these products and determine the assembly tasks and approach directions they present, as was done in our previous reasearch. Note new tasks or tool types. With this further insight, try to redefine the tasks so as to be less anthropomorphic and more mechanistic, so that a range of generic workstation requirements can be mapped out.

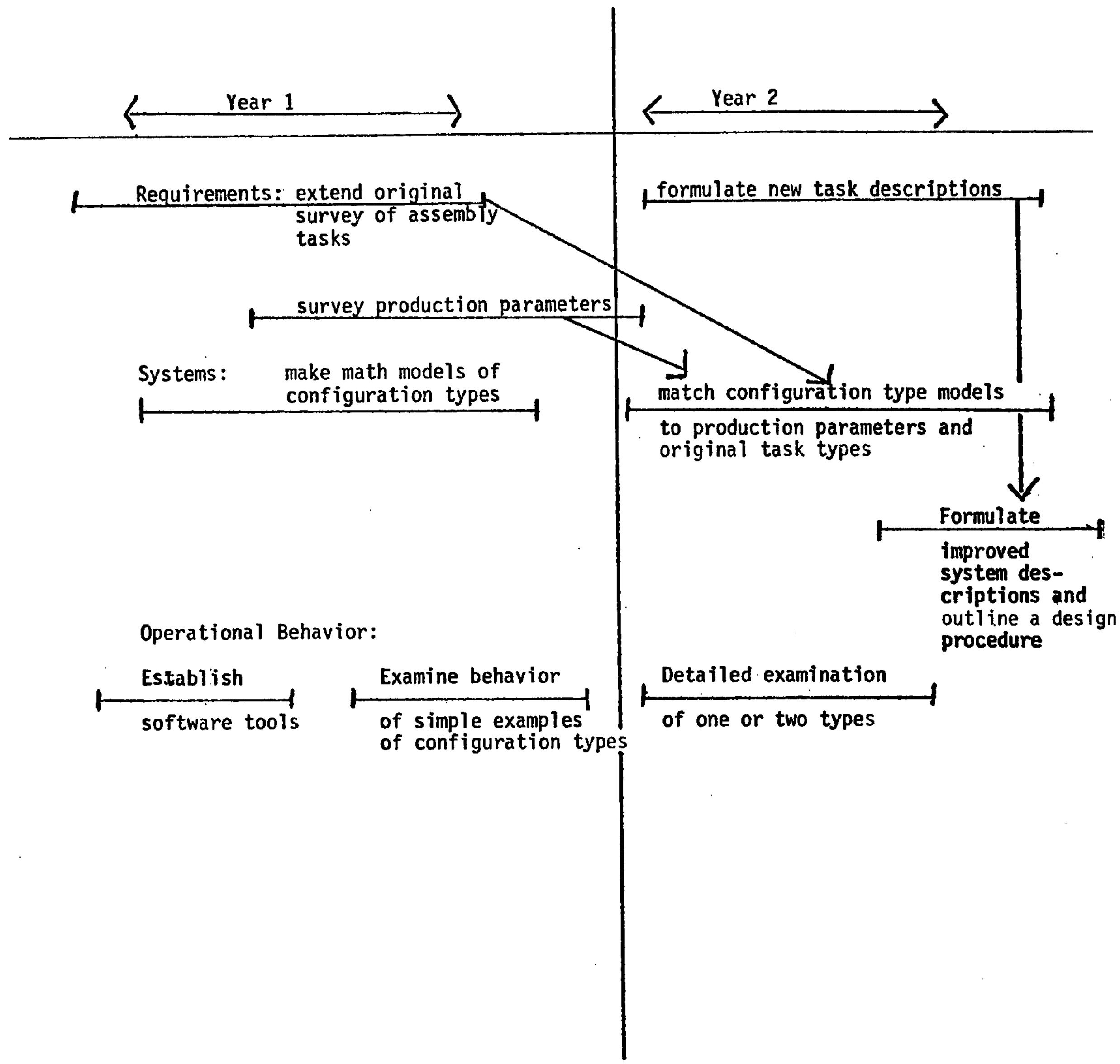
In addition, determine the range and mix of production parameters for these products. It is so often stated that "75% of all US production is in batches of 50 units or less". We would like to gather a little data on this point, although a large scale effort is clearly beyond our scope. But current batch sizes and model mix are determined to some extent by the limitations of existing technology, and the opportunities for new technology are limited by the range of existing production practice. So some base data will be gathered in the hope of shedding light here.

2. Results from task 1 will be used in task 2 to indicate what an assembly system should be prepared to do in terms of assembly operations, production rates, model mixes, etc. These will be matched against five or six basic system configuration types, tentatively to be chosen from those in Figure 1.

An operations research model, proceding along established analytical lines, will be made of several of these systems types with the goals of quantifying the options and determining what makes a good match to the requirements. If possible, a design procedure for each chosen system type will be formulated.

3. The result of task 2 will be performance descriptions which can be analyzed and simulated for their operation behavior. This step is essential because some of these configuration types may have grave operational drawbacks under the conditions of assembly(short unit operation times, for example). Second, certain types may be more robust than others in the face of changing circumstances and this robustness must be properly expressed so that it can be traded off against initial capital cost.

On this page is the schedule. Staff and students from the MIT Sloan School of Management are on the project team. Other industrial partners are welcome.



SCHEDULE

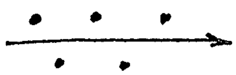
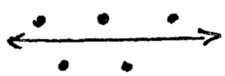
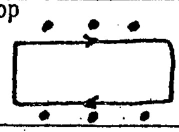
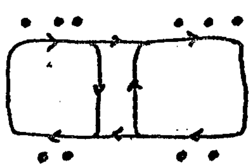
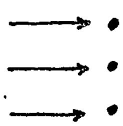
Station Types / Transport Types	Each does a special function (e.g. screws) or task type	Each does a few operations but not the whole product	Each can in principle do the entire product
One way serial line 	an accident if it works - won't do a mix of models	Westinghouse's idea — won't do a variety of products or a wide mix	GM's idea - seems over-designed but can be rebuilt into a new line easily
Two way line 	traffic jam ? Caterpillar's FMS is this type Also ROTA	traffic jam? lots of in-process inventory	Why do it?
Loop 	Ingersoll Rand's FMS is this type ("shopping center")	Kondoleon's idea, sort of	Why do it?
Multiloops 	Allis Chalmers and PRISMA FMS are this type Extra transport flexibility is needed here	Maybe a good match of station and transport	Transport flexibility is not needed here
Parallel 	Not relevant to general assembly	Unimation's idea (one station only) Multiple units show no economy of scale	Unimation's idea? ("Toll plaza") No economy of scale but lots of redundancy

Figure 1.

EXPLORATORY STUDY OF CONSTRAINTS ON DESIGN

BY FUNCTIONAL REQUIREMENTS AND MANUFACTURING

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PROGRAM OBJECTIVE - The primary emphasis of the MIT research is on the basic understanding of design decisions and the design decision making process that affects the subsequent manufacturing process. Of all the decision making processes involved in manufacturing, design decisions have the most far-reaching effects on manufacturing, efficiency, and product quality. Yet very little is understood as to how decisions should be made which lead to "good" designs and to the effects of design decisions on the overall manufacturing system. A "good" design is one which performs its function well, is easily manufactured, and withstands the test of time.

Two approaches exist for system optimization: algorithmic and axiomatic. The algorithmic approach requires an understanding of the data base for each element of the manufacturing system as well as the interactions among the separate elements. At present, neither requirement can be satisfied. In particular, present-day techniques for handling large data bases are inadequate. In fact there seem to be limitations on data processing arising from the number of variables that can be handled within a reasonable time period due to the limitations imposed by nature on the maximum possible rate of data handling.

A more promising method appears to be the axiomatic approach. The first step in manufacturing a product is the design of the product which satisfies the functional requirements and constraints. A functional requirement is defined as the specification of an independent characteristic which an acceptable solution must exhibit; with each functional requirement is associated a tolerance which defines the margin of error allowed. The satisfaction of the functional requirements must be compatible with each constraint specified, where constraints establish the boundaries within which acceptable solutions must be found. The decisions made in designing a product have a significant effect on the subsequent elements of the manufacturing system. For example, a product design, once crystallized, constrains the choice of processing methods and assembly techniques. The degree and nature of the constraints imposed on the processing methods by design determine whether the use of a new process is mandatory or if one of the existing methods is permissible. Subsequent steps in manufacturing are similarly affected. Conversely, constraints on assembly techniques and decisions for subsequent processes also affect the original design of the product.

Notwithstanding the importance of these decisions on manufacturing productivity, they are currently done empirically. Little is understood about the decision making process and the evaluation of the quality of these decisions. Nevertheless the fact is that empirical decisions often lead to the "right" or "good" design rather than "wrong" or "bad" designs. This suggests that there exist underlying design "truths" which good designers make use of. In other words, there exist axioms which govern the decision-making process. If these axioms can be formalized and their corollaries derived, then it should be possible to establish a scientific basis for guidelines in manufacturing design.

The role and power of manufacturing axiomatics can best be appreciated by comparing it with thermodynamics. Although thermodynamics is often thought of in terms of steam engines and other power-generating equipment, it is in reality a powerful scientific tool whose axioms enable us to define and deal with two important, fundamental concepts: energy and entropy. The ultimate goal of the MIT research on manufacturing axiomatics is to identify the fundamental design and decision concepts, to systematize a set of axioms for use in decision making, and to quantify characteristics for measuring the efficacy of decisions.

The specific purpose of the research project is to provide a fundamental understanding of the design decision-making process and thereby establish basic principles by which design decisions can be made, using an axiomatic approach to design and manufacturing. Specifically:

1. To verify the validity of the present preliminary set of hypothetical axioms and to create new axioms if needed.

2. To determine the effectiveness of axioms in making design decisions by developing and evaluating specific designs based upon the axioms.

3. To understand the role of decisions in the design context and investigate how decisions can be put on a quantitative basis.

4. To establish methods of quantifying information and study the relationships among axioms, information, entropy and decisions.

5. Investigate whether decisions and information can be defined in terms of axioms (just as the concepts of entropy and energy are defined by thermodynamic axioms).

PROGRAM ACHIEVEMENT - The work done prior to September 1977 was summarized in a paper by Suh et al. and presented at the ASME Winter Annual Meeting that year. It was the first publication on this new approach to the design of manufacturing systems. The authors introduced axiomatics as an alternative to the traditional "algorithmic" design procedure, the latter often requiring exhaustive searching of massive data banks or design alternatives. Seven hypothetical axioms were posed as a point of departure for a heuristic investigation which was to include case studies of a lathe and an air compressor. Eight corollaries were also derived, and several examples given.

RESEARCH RESULTS SINCE THE SEPTEMBER 1977 REPORT - An effort was made to question through case studies the basic notion of axiomatics and the definitions adopted earlier [1]. A critical application of the axioms has resulted in a reduction of the original seven axioms to six in the CIRP paper [2], and then further to two. The axioms were condensed because there were apparent among them only two independent ideas. With two exceptions noted below, the original "axioms" are directly deducible from the two stated here and are now considered corollaries. As in thermodynamics, the axioms are perhaps too general for direct application, and the corollaries are the more functional tools.

The results of the past year's research are reported below in four sections. The first describes the content in which axiomatics is considered. The next two sections present the new axioms and the corollaries respectively; and the fourth section describes information in more detail.

1. Axiomatics in the Design Process* - Let us consider a typical design process. The perceived needs are first translated into functional requirements (FR's) and the constraints (C's) imposed on the design by factors external to the perceived needs. Then, ideas are generated which may satisfy the functional requirements and constraints. Initially a good design practice is to minimize the considerations to the most important functional requirements and constraints. When a satisfactory solution is found for the coarse set of functional requirements and constraints, the solution is refined by expanding the set. This process may be envisioned as a "design helix" since each iteration improves the design.

The problem in design arises because the solutions proposed to satisfy the functional requirements and constraints cannot be evaluated readily, especially if the designer does not have a wealth of experience (i.e., a large data base) from which to draw. Even if he does, the decision making process is risky at best. There must be a means of checking whether the proposed solutions are indeed good design solutions without having to fabricate and test them. This is where axioms can play a useful role.

Axioms can be used to eliminate inferior solutions to a given problem by checking whether the proposed solutions violate any axioms. Axioms can also be used to evaluate the solutions quantitatively by providing tools with which to rank order them. In terms of manufacturing axioms, the axiom which deals with maintaining independence of functional requirements, for example, may be used to eliminate solutions which couple them. The axiom that deals with minimization of information content can be used to quantify the information contents of proposed designs for rank ordering.

It is important to recognize that the manufacturing axioms must be used within a rigid structure established through a common definition of terms and methodology. For example, the definitions of FR's and C's must be rigidly adhered to, and once the FR's and the C's are defined, the solutions which satisfy them are the solutions to the specified problem. If it is desired to improve the design, the solution process requires that the FR's and the C's be refined. Then there can be corresponding solutions which satisfy the perceived needs better. What the iteration process (of refining the FR's and the C's) does is to improve the definition of the problem in terms of the perceived needs, and to provide corresponding solutions. In this sense, it is similar to solving differential equations for different sets of boundary conditions.

Axiomatics does not obviate creativity, but it assists the creative process by channeling creative thought . For example, the axiom on maintaining the independence of functional requirements would eliminate any ideas which violate the axiom, thus allowing for the generation of candidates which have high probability of success.

Between each stage of design, including the initial stage of defining functional requirements and constraints, there flows information. Information coming into each step of the design process is modified by the decisions (some of which are axiomatic) made at that stage. At every stage of the process, information is certainly lost (equivocation) and spurious information (noise) is introduced. Functional requirements and constraints constitute a type of information which is generated from perceived needs. This step is equivalent to a coding of the problem based on an arbitrary set of values.

The role of manufacturing axiomatics may also be presented within a deterministic structure. Here the process of design starts from a UNIVERSE of possible design solutions. In the framework of design selection, this universe may be assigned Level 0. Projected on this level is the problem statement in the form of FR's and C's. The imposition of FR's (which represent Screen 1) to the design universe results in a smaller set of candidates, denoted Level 2. At this point a screen of constraints is applied, yielding a finer Level 2 of ACCEPTABLE solutions. Since these solutions fulfill both the FR's and C's, they are mechanically acceptable solutions to the given problem.

*For detailed background on manufacturing axiomatics, see the original paper [1]

Next the set of axioms and corollaries are applied, thereby resulting in the set of TERMINAL solutions, Level 3. The function of axiomatics may end at this level, since the terminal solutions have been optimized in an engineering sense: these solutions satisfy the problem by fulfilling the FR's and C's, and are further optimized in terms of the axioms. However, if the solution obtained differs from the perceived needs, it indicates that the initial formulation of functional requirements and constraints was not sufficient. In some cases these may be more than one solution that satisfied the FR's, C's, and the axioms. In order to choose the best solution from these, the functional requirements and constraints must be redefined or new ones added.

The final phase of the optimization process may be a straight-forward selection task using the established techniques of decision analysis. Although each terminal solution fulfills the FR's and abides by the C's, the individual levels of constraint attributes will vary from one design to the next: these may be evaluated for relative merit.

EXAMPLE: Two compressor designs A and B both fall within the minimum established constraints of size and noise. But A is noisier than B, which in turn is bulkier than A. Here a laboratory technician might prefer to use A, while a hospital technician might prefer B.

The final stage, Screen 4, may be involved for some problems. If so, the decision maker must then draft a preference structure (in the case of certainty about attribute levels) or a utility function (for noncertainty). These are established for each attribute within its permissible range of variation and used to identify the best solution for the given problem.

2. Axioms - Before the axioms can be stated, the definitions of functional requirements and constraints must be understood. They are defined as [1]:

1. Functional requirements: the desired set of independent specifications that solutions must meet.
2. Constraints: factors which establish boundaries on acceptable solutions.

The functional requirements are, by definition, independent. A primary goal of design is to keep them independent in a solution. The independence of the specified functional requirements should be verified before solutions are sought.

The first axiom considers the independence of functional requirements and constraints and stipulates that FR's must be satisfied independently in any acceptable design solution.

Axiom 1: Maintain the independence of functional requirements and constraints.

Axiom 2: Minimize information content.

Axiom 2 states that the simplest way of satisfying functional requirements and constraints is the best.

3. Corollaries: Many corollaries can be derived from the axioms. As in thermodynamics, they are the actual tools which are used in system analysis and design. Here only four of the most general and most important corollaries are treated. All four were originally posed as axioms [1], but redundancies have been recognized and two independent ideas have filtered out as the axioms presented above.

Corollary 1: Minimize the number of functional requirements and of constraints.

Each functional requirement and constraint carries information into a design. Axiom 2 requires minimization of this information. Unnecessary functional requirements and constraints are a result of noise or inefficient coding during need perception.

Corollary 2 : Decouple or separate parts or aspects of a solution if functional requirements are coupled or become interdependent in the designs or processes proposed.

This powerful corollary derives from Axiom 1. Its implications are much deeper than they at first appear. There are situations where coupling is inevitable. Pressure and temperature of a gas, for example, are inherently coupled, and any adiabatic system which changes the pressure of a gas by mechanical work must also change the temperature. If certain pressures and temperatures were both functional requirements of the system, an additional element (e.g. temperature control) must be added to regain independence. This task may be quite difficult unless tolerances on pressure or temperature or both are kept loose. When possible, coupling should not be allowed in the first place.

Corollary 3: Conserve materials and energy.

Implicit in this and all corollaries is the understanding that neither axiom be violated; "conserve" here means use no more than necessary. Information is required for processing any material or energy, so wasting either of these violates Axiom 2.

Corollary 4: Integrate functional requirements in a single part or solution if they can be independently satisfied in the proposed solution.

This corollary actually follows directly from Corollary 3 above and carries with it a caveat about coupling. (Figure 1 indicates how the corollaries derive from the axioms.)

Integration refers to the combination or juxtaposition of physical or conceptual quantities. This may or may not result in COUPLING, which refers to the combination of functions in which one FR interferes with the execution of another. These concepts will be illustrated through concrete examples in Section 6.

4. Types of Information - The information required for the evaluation of manufacturing systems may be classified into DECISION and SYSTEM information (see Fig. 2). The former (I_D) refers to the information needed for task evaluation and conceptual decision making; the latter (I_{sy}) refers to the information describing the physical system or apparatus. One subdivision of I_{sy} is MICROinformation (I_μ) which specifies information on a microscopic scale. To illustrate: consider two blocks of metal, one heat-treated and the other not: they differ only in this respect. The gross geometric information may be the same in each case, but microinformation obviously is not. The first block contains more microinformation than the second, since the crystalline structure has changed from a homogeneous to a heterogeneous condition.

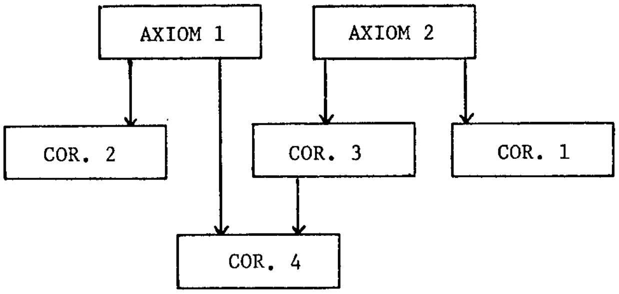

FIGURE 1: DERIVATION OF COROLLARIES

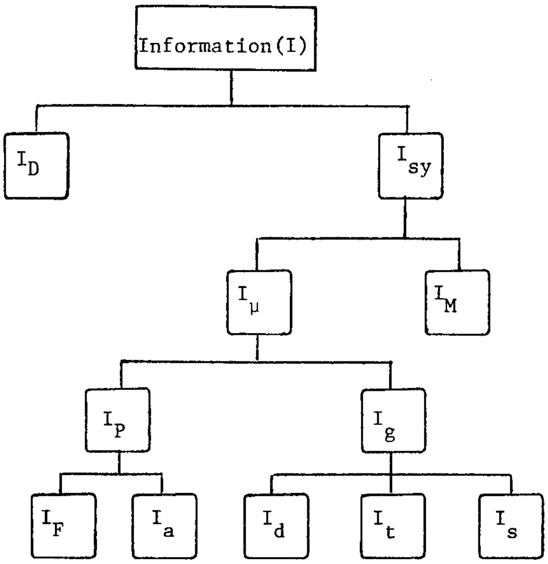

FIGURE 2: TYPES OF INFORMATION.

The second type of system information is MACROinformation I_M referring to the data due to the gross characteristics of a product or process: it may be dubdivided into processing and geometric information.

PROCESSING information (I_P) indexes the data required for fabrication and assembly. FABRICATION information (I_F) refers to the creation of the actual physical objects, whereas ASSEMBLY information (I_a) refers to the unification of the parts into a composite whole.

The other aspect of I_M is GEOMETRIC information (I_g) pertaining to the form of the final product. The three subdivisions of I_M are dimensional, tolerance, and surface finish information (see Fig. 3).

DIMENSIONAL information (I_d) refers to the information required to specify the gross dimensions of an object. The "blocks" of data used to generate dimensions for numerical-control production may adequately monitor the I_d index. (Example: Generating a hole would require a block of information, and so would specifying a flat cut. On the other hand, an external curved surface would require one block per quadrant -- as a result four blocks would be used for a full circle.)

TOLERANCE information (I_t) relates to the tolerance within which a dimension is acceptable, and is defined as

$$I_t = K_t \ln \frac{D}{\Delta D}$$

where D is the dimension and ΔD the tolerance. The constant K_t is a weighting function that describes the difficulty associated with a specific process. A standard value for the tolerance in machine production is 0.005 inches. This definition of tolerance information is the same as that used in the information theory [3].

SURFACE finish information (I_s) must be taken into account when a fine surface finish is needed. It is defined as

$$I_s = K_s \ln \frac{s_o}{s}$$

where s is the specified finish and s_o the standard finish obtainable from a given operation (e.g., turning) without any extra effort. For many machining and milling operations s_o is 64 microinches. When a finish of 4 microinches is specified, for example, the surface finish information is

$$I_s = K_s \ln \frac{64}{4}$$

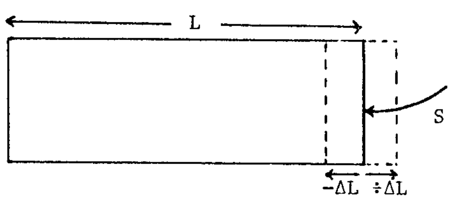

FIGURE 3: GEOMETRIC INFORMATION.

When a designer does not stipulate any particular surface finish, the standard finish is assumed for s, and the I_s term disappears:

$$I_s = K_s \ln \frac{s_o}{s_o} = 0$$

For each workpiece surface, the total geometric information is then given by the sum of the previous three:

$$I_g = I_d + I_t + I_s$$

which may also be stated as

$$I_g = I_d + K_t \ln \frac{D}{\Delta D} + K_s \ln \frac{s_o}{s}$$

Information and Decisions - Recalling the objectives of manufacturing axiomatics, decision rules are sought which can be used quantitatively to focus alternatives and improve the quality of the overall design decisions. Since a major facet of the manufacturing process involves the identification and evaluation of decisions, a critical task for the success of the axiomatic approach is the development of a quantitative formulation of the entire decision making process. Development of the formulation begins with the following observations:

1. Decisions are uncertain.

2. Information about a decision increases the likelihood of making the best choice.
3. Decisions that have been made provide information for subsequent decisions.

A decision, then, is a conceptual entity which requires certain information as an input and makes available certain other information as an output. Decisions and therefore design are probabilistic. That is, one can never be 100% sure, at the time a decision is made, that it is the right one. In addition all real physical processes are to a degree, stochastic. The necessary specification of tolerances for system parameters implies probability density functions since parameters cannot be obtained exactly but should, with high probability, be within the specified tolerances.

Extensive work has been done in information theory considering information as a logarithmic accounting tool for handling probabilities. This final observation offers a means of tying the earlier observations together by considering decision making from an information theory perspective. Before addressing the decision model, some terms must be defined. First, a somewhat restrictive definition must be imposed on the word "information".

Information here is considered in the communication sense. Information, or "negentropy", is intuitively the opposite of entropy in that additional information about a system decreases its randomness or uncertainty. Shannon [3] defined an entropy, or "confusion", functional:

$$H = K\Sigma q_i \ln q_i$$

which is positive for probabilities q_i less than 1 (K is a constant). Information received is the difference between the entropies before and after receipt of information; i.e. information decreases entropy as stated above.

An important distinction must be maintained when considering information this way. Information here is only a numerical accounting of probabilities; while it often reflects knowledge about a situation as in normal usage, there is no definitive connection between information and knowledge. More importantly, perhaps, information has no explicit value. That is, the quantity of information transmitted should be calculated as the same number by any two people even though the value of that information may be considerably different. An extension of this point is that bad (incorrect or uncertain) information counts as much as good information, and the two are indistinguishable. A juxtaposition of good and bad information is called noise.

As depicted in Figure 4, a "need" can be considered an information source. Perception of the need in terms of functional requirements and constraints then represents a coding of that information. The decision making process channels the information toward the final design. Also represented in the figure are information being lost (equivocation), and superfluous information being added (noise). Inclusion of these last two quantities is a statement that people are unable, in general, to properly specify a need and make the proper decisions required to produce a design exactly meeting that need. The key feature of Figure 4, however, is the notion of axioms entering at the decision stage. The implication is that information can be eliminated or added based on decisions made by the use of axioms.

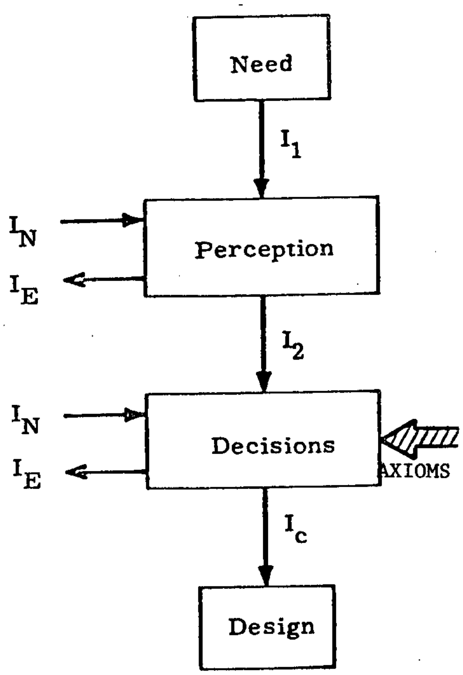

FIGURE 4: AN INFORMATION THEORY MODEL OF DECISION MAKING AND THE DESIGN PROCESS.

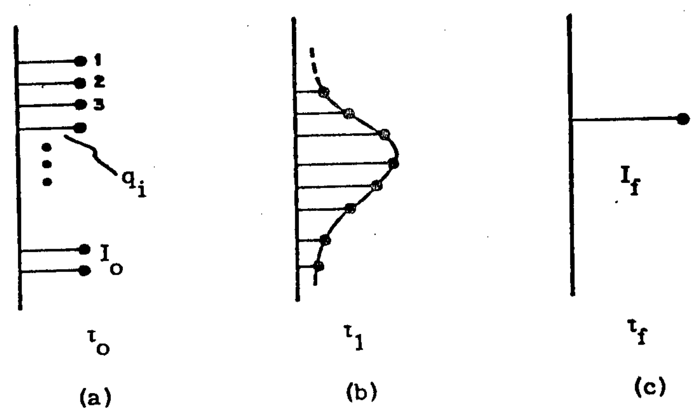

FIGURE 5: STATES OF A DECISION AT THREE DIFFERENT TIMES

As an example of one such decision, take the choice of material. The state of this decision is represented at three different times in Figure 5. The points are possible alternatives, and q_i is the normalized apparent correctness of choice i; q_i is treated as a probability. It is not known how to quantify information such as functional requirements and constraints; in fact all functional requirements probably do not carry the same information. The information can be quantified, however, by observing its effect on the state of the decision. Consider as a thermodynamic analogy a piston and a cylinder containing a gas in Fig. 6. Heat Q_i added to that system cannot be measured explicitly, but it can be calculated by

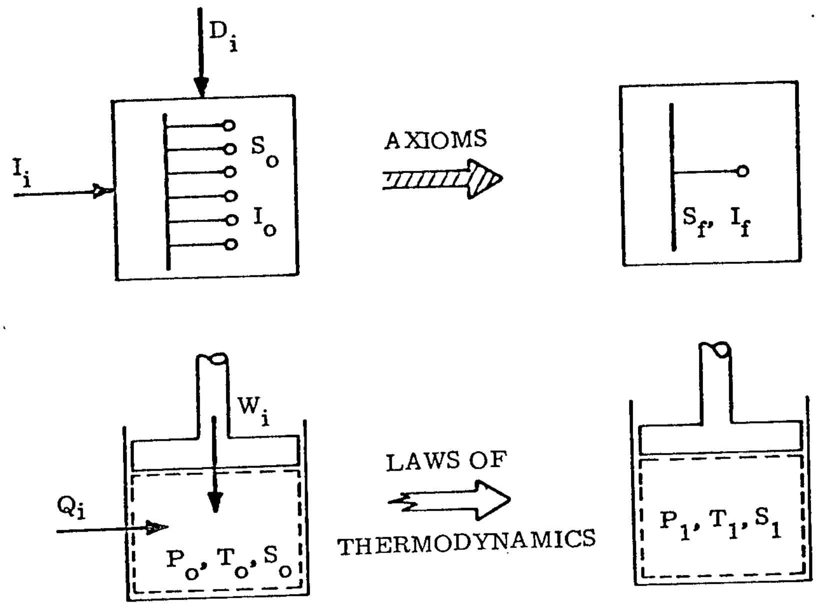

FIGURE 6: A THERMODYNAMIC ANALOGY OF THE DECISION MAKING PROCESS.

observing its effect on the system. In fact, Q_i is directly related to the change in entropy of the system by the formula $\Delta S = Q_i/T$. However, heat need not be added intentionally because work, in a less obvious way, can change the entropy and the state of a system. The laws (axioms) of thermodynamics govern that change. Examination of the changes of state of a decision indicates that the addition of information is not the only way to effect a change. The actual making of the decision, even in the absence of sufficient information, also causes a change of state in a manner analogous to the addition of work to a thermodynamic system. If I_o is zero as discussed below pertaining to Figures 5(a) and 6, then I_f is equal to the entropy change $(S_o - S_f)$. Notice that the decision states of Figure 6 must not be states of an isolated system since entropy decreases (the final state is much less random). The information I_i and the decision itself D_i are the external agents.

Returning to the single decision of Figure 5: of all the information available as input to that decision, very little is pertinent -- and even less is probably used. Relevant information not used is considered lost to that decision (equivocation) although that information may still be used by other decisions. In addition, some information may be invented, or educated guesses may have to be made and will count as noise. Initially, before anything is known about the decision, there exist many equal alternatives. That is, at a hypothetical instant before the decision is considered, its state is as in Figure 5(a).

A decision made at this point would be entirely random; the information resulting would represent noise. As information becomes available in terms of functional requirements, constraints, and results of other decisions, the material decision is gradually constrained. Certain choices can be eliminated, and others begin to look less favorable as represented in Figure 5(b). Less additional information is required to make the decision now. It can be shown that eliminating alternatives or making q's less equal both have the effect of reducing the remaining information required to make the decision. Just as (a) in Figure 5 is the initial limiting situation, (c) represents the ultimate limiting case where sufficient information is available to reduce the choices to one and make the decision deterministic. In any complex decision, this case would not arise. Instead (c) would represent the decision immediately after a choice had been made. An instant before t_f choices probably would have been narrowed to only a few, some of which might still have been indistinguishable. A decision must be made at this point. That decision is the additional input which results in the final state of Figure 5. The rules governing that decision and change of state are the design or manufacturing axioms.

6. Some Examples

DUAL OPENER - A common kitchen item is a dual tool which combines a bottle opener at one end with a can opener at the other. As long as no FR stipulates that the two uses of the tool must be executed simultaneously, the requisite FR's are independent. In consequence, they are (physically) integrated but (functionally) uncoupled and therefore, do not violate Axiom 1.

FLYWHEEL - A case study for the development of manufacturing axiomatics is a 15-horsepower Ingersoll-Rand reciprocating air compressor. A study of its FR's proves the flywheel to have integrated its three

functions: fanning, inertia and torque-handling. The fanning ability may be varied by the number and pitch of the radial blades; the inertia by the mass on the rim; and the torque-handling by the geometry of the rim. Thus these FR's are integrated rather than coupled.
CYLINDER - Another component of the reciprocating compressor is the pair of first-stage compression cylinders. The three FR's are adequate wear life, pressure containment, and temperature reduction through heat transfer. The last two are coupled in theory, since the thickness of each cast-iron cylinder is used to satisfy both requirements.

However, the heat transfer mechanism happens to be dominated by the convective resistances internal and external to the cylinder: the conductive resistance of the metal accounts for less than 4% of the total. As a result, the two FR's are coupled in theory but almost independent in practice.

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IDENTIFYING THE MATERIAL HANDLING RESEARCH NEEDS FOR DISCRETE PARTS IN THE AUTOMATIC FACTORY

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PROGRAM OBJECTIVE - Currently, material handling research appears to represent a passive response to short-term needs, rather than an active response to long-term challenges. Material handling equipment developments have tended to be evolutionary, rather than revolutionary. Many of the "new" equipment concepts introduced to the U.S. market were developed originally in Europe. CAD/CAM research in the U.S. has concentrated on the product design and process design functions of manufacturing; little, if any, consideration has been given to either the schedule design function or the process design function as it relates to material handling. The success of the integrated manufacturing facility is highly dependent upon each function being performed effectively. Under the current set of research priorities, little attention is being given to the material handling research needs of the automatic factory that manufactures discrete parts.

The objective of this research effort is to identify specific directions for material handling research. In order to achieve the research objective a workshop will be conducted. The workshop will provide directions for research such that material handling will not be the bottleneck in the automatic factory of the 1990's.

PROGRAM ACHIEVEMENT - Since the research contract was awarded after the last report meeting at MIT in September 1977, this report covers all progress to date. The workshop will be held at Georgia Institute of Technology during the four day period January 29 - February 1, 1979. An advisory committee has been formed, consisting of Dr. Wilbur L. Meier (Purdue University), Dr. Donald T. Phillips (Texas A&M University), and Dr. Richard C. Wilson (University of Michigan). The workshop will address the material handling requirements of the functional areas of receiving, storing, processing, warehousing, and shipping in the automatic factory. The research needs will focus on identifying the academic disciplines required, as well as the technological gaps that exist. Although the program for the workshop has not been finalized, a tentative program has been developed; it is anticipated that the final program will be available at the time of the September meeting at Purdue.

On January 29 the workshop will begin with an address by Dr. Joseph Pettit, President of Georgia Institute of Technology and a member of the National Science Board. Dr. Bernard Chern will describe the challenge to material handling presented by the automatic factory. Perspectives on material handling research will be provided by a leader from the material handling industry. Several speakers from Europe will address the subject of CAD/CAM and Material Handling.

On January 30 the workshop will focus on CAD/CAM and material handling in the United States. Representatives from university, government, and industry research groups will give presentations. The intent is to provide the workshop participants with a feel for the state-of-the-art in the U.S. as compared with Europe.

On the morning of January 31, it is planned to provide status reports on material handling research programs at four universities. In the afternoon, the attendees will be divided into discussion groups and will address the material handling research needs. The groups will report their findings and a composite list of needs will be formed.

On February 1, new groups will be formed and priorities will be assigned to the research needs. The groups will report their findings and a composite prioritized list of material handling research areas will be generated.

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